Transformation of the Swiss Energy System for a Net-Zero Greenhouse Gas Emission Society

Results from the Joint Activity Scenarios & Modelling

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Executive Summary

Switzerland aims at reducing its greenhouse gas emissions (GHG) to net-zero by the middle of the century. Reaching this ambitious target requires important changes to the energy system. In the Joint Activity Scenarios and Modelling (JASM), modelling teams from the eight Swiss Competence Centers for Energy Research (SCCER) worked together to analyze alternative configurations of the energy system and possible pathways to reach this goal. This approach is different from other efforts to define a long term energy strategy for Switzerland, as it is based on the combined output of the Swiss energy research community. To achieve this, we developed and used a framework that soft-links a variety of models from the project partners.

Future configurations of the Swiss energy system are influenced by uncertainties on demographic and economic growth, technological development and acceptance, market designs and global climate change. However, despite these uncertainties, we were able to derive a robust narrative for a net-zero Switzerland, that identifies those elements and technologies that will very like be a part of our future energy system. This narrative includes the following specific recommendations for policy measures and actions today.

Heating. The heating sector will largely abandon the use of fossil fuels. The dominant technology for domestic heating are heat pumps, aided by the combustion of wood. Thermal grids will grow strongly and are fed by waste incineration plants and large scale heat pumps. Alternatives are district heating and cooling systems with decentralised small scale heat pumps. For industrial heat, we see a switch to medium and high-temperature heat pumps, electric heaters, and hydrogen for high temperature levels. Additionally, we find that medium temperature heat sources such as geothermal or solar thermal will play an important role for all these applications. Generally, there is a trade-off between a switch to new energy sources and efficiency measures that directly reduce heat demand in the residential and industrial sectors. We find that in an overall cost optimization, these efficiency measures are generally cost-effective to reduce related CO_2 emissions.

Mobility. Private passenger transport must be largely electrified. Incentives will be needed to foster the installation of charging stations in the private and public space. Electrification becomes also increasingly important for light duty vehicles for freight transport services. If battery-electric mobility is not possible due to heavy load, range or consumer preference limitations, hydrogen fuel cell vehicles must be deployed or alternatively synthetic hydrocarbon fuels. Clearly, direct electrification of transport and electricity-based fuels represent the majority of electricity consumption growth in future.

CCS and negative emissions. To reach net-zero GHG emissions, the energy sector must avoid CO_2 emissions where possible and compensate emissions from other sectors where abatement is more challenging, such as agriculture or some industrial processes. This requires the application of CO_2 capture and storage (CCS) on waste incineration and cement plants, and the deployment of technologies to produce negative emissions, such as biomass combined with carbon capture and storage (BECCS). BECCS technologies include anaerobic digestion, wood gasification to methane or hydrogen, or wood combustion with CCS to produce electricity and heat. Without CCS the net-zero ambition of Switzerland cannot be achieved.

Electricity supply. Electricity demand increases due to the electrification of heating and mobility, reaching 70–90 TWh/a in 2050. After the nuclear phaseout, the electricity that was produced with nuclear power plants will mainly come from renewable sources, mostly photovoltaics (15–30 TWh/a) and wind, plus some thermal power plants and imports. The last two will be especially relevant for the winter months when solar generation is low. The relevance of energy imports will highly depend on the market design, the climate policies abroad and political decisions concerning security of supply.

Electricity storage. Switching from reliable nuclear power to fluctuating renewables poses challenges to the energy system. This can be alleviated to some extent by storage and flexibility technologies.

First priority will be electricity storage, from batteries at the lowest voltage level to pumped hydro power stations. Given the limited storage volume, these technologies can tackle the day-night cycle, especially in the summer months. Flexible regulated hydropower plants that can complement PV generation are also required. Increasing the volume of hydro reservoirs by dam heightening will help to increase winter electricity production.

Flexibility and sector coupling. Coupling the heating demand with the electricity production gives additional flexibility and storage options to deal with the fluctuation of renewable electricity. These include: Large scale heat pumps at district heating level that charge a seasonal thermal energy storage during the summer months; or electrical heaters with short-term thermal storage that supply process heat. Also the conversion of electricity to hydrogen via electrolysis, coupled with short-term or seasonal storage, will play a role. In mobility, the efficient integration of Grid-to-Vehicle and Vehicle-to-Grid schemes provides a number of advantages to the power system. The need for flexibility would also require a market opening, which entails a variety of opportunities for centralised storage (including new solutions based on hydrogen and e-fuels), for flexible consumers (individual ones or those collectively offering their capacities through aggregators) with decentralised storages and smart demand technologies, and for energy producers who can be integrated via peer-to-peer trading.

The future energy system. Despite the importance of electrification for heating and mobility, the future is not simply all-electric. Biomass plays an important role as a source of chemical energy and to produce negative CO_2 emissions via BECCS technologies. Hydrogen can help to decarbonize transport, power and heat, and can generate negative emissions when produced from biomass. CO_2 needs to be captured and stored wherever possible. Since domestic storage options have not yet been identified at the required scale of 10–20 Mt_{CO_2}/a, an integration with an European CO_2 transport and storage infrastructure is of paramount importance.

Continued research on holistic analyses on the restructuring of the energy system. Given the ambitions of the energy transition, which involves technical, economical, environmental, political and societal challenges, further collaborative research addressing these challenges in a systematic and integrated way is needed to support decision-making. Energy modelling and holistic scenario analyses play a pivotal role in this not only by providing quantitative insights but also by connecting various research domains which is essential to address the fundamental changes of the energy system ahead.

Acronyms and Abbreviations

ARE	Amt für Raumentwicklung (Federal Office for Spatial Development)
BAFU	Bundesamt für Umwelt (Federal Office for the Environment)
BAU	Business As Usual Scenario
BFE	Bundesamt für Energie (Swiss Federal Office of Energy)
BFS	Bundesamt für Statistik (Federal Statistical Office)
CCS	CO_2Capture and Storage
CDD	Cooling Degree Days
CHP	Combined Heat & Power
CLI	Climate Policy Scenarios
EMPA	Eidgenössische Materialprüfungsanstalt (Swiss Federal Laboratories for Materials Science and Technology)
EPFL	École Polytechnique Fédérale de Lausanne (Swiss Federal Institute of Technology in Lausanne)
EPOL	Energy Policy Scenarios
ERA	Energy Reference Area
ETH	Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology in Zürich)
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GSHP	Ground Source Heat Pump
GVA	Gross Value Added
JASM	Joint Activity Scenarios & Modelling
HDD	Heating Degree Days
HP	Heat Pump
HSLU	Hochschule Luzern (Lucerne University of Applied Sciences and Arts)
PSI	Paul Scherrer Institut
PV	Photovoltaics
RCP	Representative Concentration Pathway
SCCER	Swiss Competence Center for Energy Research
SCCER-SoE	SCCER Supply of Electricity
SES	Swiss Energyscope
STEM	Swiss TIMES Energy System Model
UNIBAS	Universität Basel (University of Basel)
UNIGE	Université de Genève (University of Geneva)

kWh	kilowatt-hour
GWh	gigawatt-hour, 1 GWh = 10^6 kWh
TWh	terawatt-hour, 1v TWh = 10^9 kWh
PJ	peta-joule, 1 PJ = 0.277 TWh, 1 TWh = 3.6 PJ

Table of Contents

1 Joining forces: the JASM Framework

JASM is a joint activity of several modelling teams within the eight Swiss Competence Centers for Energy Research (SCCER). The aim of JASM is to define and analyze scenarios for reaching net-zero greenhouse gas (GHG) emissions in Switzerland by the middle of the century. The JASM framework consists of energy-system and sectoral models using a consistent set of drivers and scenarios definitions. Whenever possible, we used the latest insights and results from the respective SCCER.

1.1 Swiss Climate Goals

In summer 2019, the Swiss Federal Council announced its ambition to reduce Swiss greenhouse gas (GHG) emissions to net-zero by 2050 (Swiss Federal Council, 2019). This includes emissions from the energy system, agriculture, waste and LULUCF (land use, land-use change, and forestry). On 9th December 2020 Switzerland submitted its revised National Determined Contribution to the United Nations. However, the net-zero GHG emissions target – and the question of whether part of the emissions can be compensated abroad – is still under discussion in the political arena. Nevertheless, the objective of JASM was to find options on how Switzerland can realize this net-zero GHG emissions target from the perspective of the energy system.

The Swiss CO_2 emissions from the energy sector (fuel combustion for energy conversion, manufacturing, transport, commercial and residential sectors plus the emissions from the calcination process in cement plants) amounted to 38.3 Mt_{CO_2}/a in 2015. The total GHG emissions (including CH_4, N_2O and others) were 47.9 Mt_{CO_2eq}/a (BAFU, 2020). The largest contribution to the difference of 9.6 Mt_{CO_2eq}/a is from agriculture with 6 Mt_{CO_2eq}/a. A recent report by the Swiss Federal Office of the Environment estimates that by 2050 the non-energy emissions that are difficult to avoid are 2 Mt_{CO_2}/a for cement production and 4.8 Mt_{CO_2eq}/a for agriculture/food production (BAFU, 2020). Therefore, we analyzed targets on energy-related CO_2 emissions between 0 Mt_{CO_2}/a (assuming some compensation abroad) and -6 Mt_{CO_2}/a (without any compensation).

1.2 The JASM Framework

Energy system models are the core of the JASM framework. They represent consider the interdependencies between supply and demand for the sectors electricity, heat and transport (Section 1.3). Energy system models are informed by the results of sectoral models that represent certain sectors in greater detail (Section 1.4). Examples are models of the residential and the industrial sector, which give investment costs for energy efficiency measures, or hydrological models that estimate the impact of climate change on hydropower generation. In Figure 1 we map the JASM modelling framework, data inputs, and the contributions from each modelling group.

For both energy system and sectoral models, we developed a set of harmonized assumptions (Section 1.5):

- drivers of energy use, i.e. population, economic growth, and climate
- resource availability (photovoltaics, wind, hydropower, and biomass)
- and technology characteristics (investment costs, conversion efficiency, etc.)

We calculated energy demand exogenously from macro-economic drivers. Here we made the simplifying assumption that the end-use demand (i.e. the useful or energy service demand) is not elastic to energy prices, i.e. it does not react to changing prices. In a second step, we determined endogenously the optimal renovation levels needed to reduce these demands by applying energy efficiency cost curves for the residential and industrial sectors (Section 3.4). In this step the energy-system models determine the optimal level of investment on renovation measures and the corresponding demand reduction.

Using the JASM framework, we evaluated scenarios that are defined along different policy dimensions including technology availability, market integration, and climate policy (Section 2).

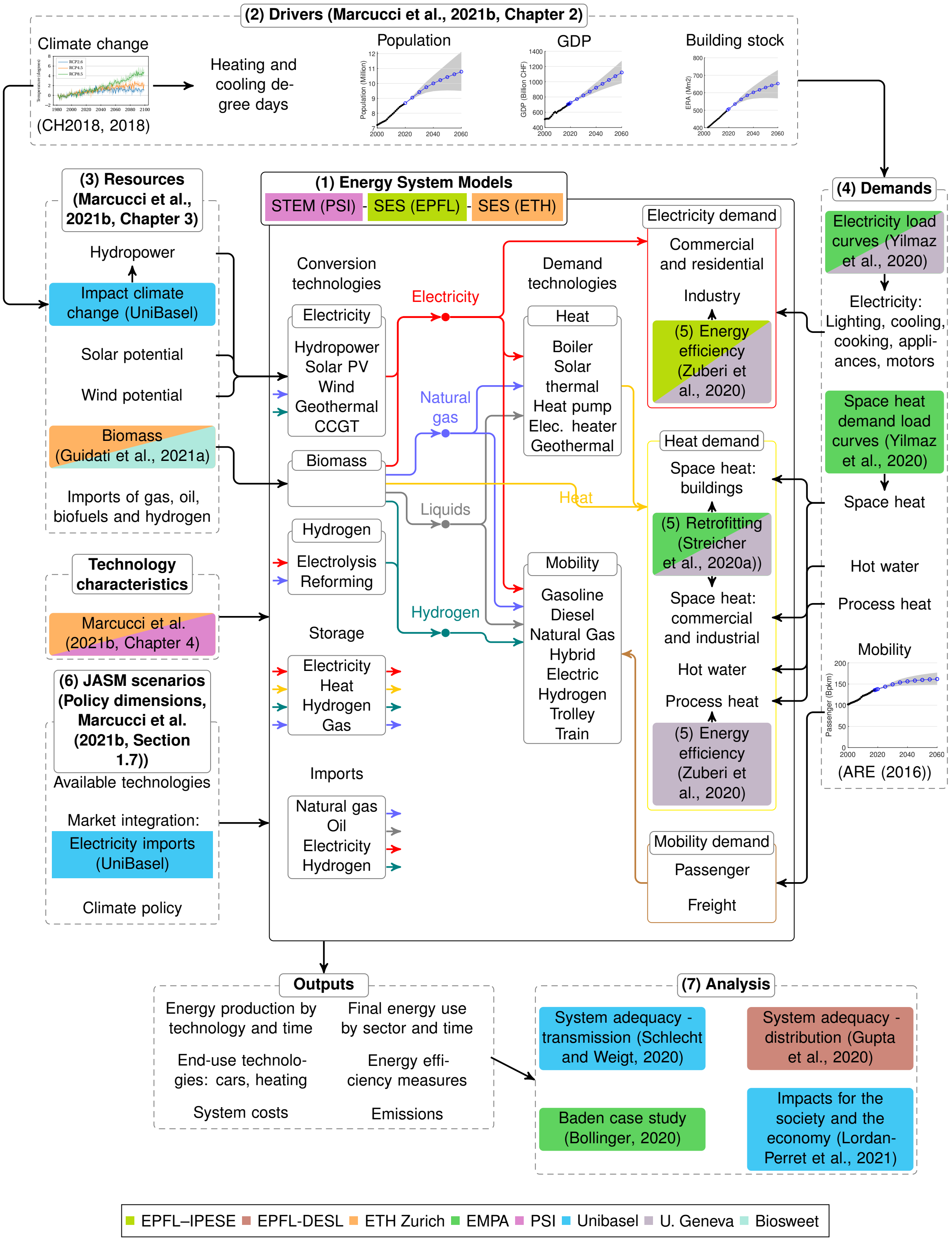


Figure 1: *The JASM framework.*

1.3 Energy System Models

The JASM framework has 3 energy system models:

1. Swiss TIMES Energy system Model (STEM, PSI) (Panos et al., 2019; Kannan and Turton, 2014),
2. Swiss Energy Scope (SES) from EPFL (Moret, 2017)
3. and ETHZ (Marcucci et al., 2021a).

STEM models the *transition pathways* in the 2020–2050 time horizon, combining long-term investment decisions with short-term operational constraints, and includes a significant level of technical details. The SES models are *snapshot models*, i.e. they provide results for one single year in the future (e.g. 2050) with a simpler representation of the energy system. We use the SES models to do uncertainty analyses with a large number of scenarios.

We intentionally use models with different capabilities in order to evaluate stable, large structural trends in technology deployment, that allow us to formulate a robust narrative of the future Swiss energy system.

1.4 Sectoral Models

The sectoral models in the JASM framework allow us to model in detail important aspects of the energy system:

Impact of climate change on hydropower production: Using Swissmod from the University of Basel (UNIBAS), we determined the effect of climate change on the inflow to hydropower plants for the latest representative concentration pathways (RCP 2.6, 4.5, 8.5) of the Swiss climate scenarios (CH2018, 2018) (Section 3.1). This work was aligned with researchers from SCCER-SoE.

Impact of climate change on heating and cooling demand: Berger and Worlitschek (2019), from the Lucerne University of Applied Sciences and Arts (HSLU), calculated the future heating degree days (HDD) and cooling degree days (CDD) for the three climate scenarios in CH2018 (2018) (Section 3.2).

Hourly load curves: Our energy system models need the hourly demand profile for energy services (in the residential, commercial, industrial and transport sectors) as input. In our JASM framework, the Swiss Federal Laboratories for Materials Science and Technology (EMPA), University of Geneva (UNIGE), and Eastern Switzerland University of Applied Sciences (HSR Rapperswil) (Yilmaz et al., 2020) estimated these hourly profiles for different sectors and weather conditions (Section 3.3).

Energy efficiency: We model the reduction of the energy demand from gains in energy efficiency based on the energy efficiency curves from UNIGE and EMPA (Sections 3.4 and 3.5). We use energy efficiency curves as inputs into our energy system models to relate potential energy savings with their cost for the industry (Zuberi et al., 2020) and the buildings in the residential and commercial sectors (Streicher et al., 2020a). This work was closely related to the SCCER Future Energy Efficient Buildings & Districts (SCCER-FEEB&D) and SCCER Efficiency of Industrial Processes (SCCER-EIP).

1.5 Harmonized Assumptions

An important value added by JASM is the fact that we harmonized our assumptions concerning macro-economic drivers, resources and energy demands (Marcucci et al., 2021b) (available at https://data.sccer-jasm.ch).

Macro-economic drivers: The JASM drivers are factors that affect energy-use but are not sensitive to domestic policies or changes in individual behavior: population, economic growth, global climate change, and technology characteristics. In the JASM framework, we define variants for the drivers to capture the range of possible futures for Switzerland: three variants (reference, high and low) for population, GDP, energy reference area, and three variants for global climate change developments (RCP 2.6, 4.5 and 8.5, based on the CH2018 (2018) climate scenarios) (Marcucci et al., 2021b, Chapter 2).

From a STEM analysis of these variants, we obtain distinct, deterministic pathways resulting from the combinations of these variants – a sensitivity analysis of the drivers on the results. The SES models instead model these variants as uncertain parameters with particular probability distributions, and conduct an uncertainty analysis with a Montecarlo sampling method.

Resources: In addition to the common drivers, we also harmonized assumptions concerning the availability of domestic resources, including hydropower, solar photovoltaics, wind, biomass, and the prices of imported fuels (i.e., gas, oil, biofuels and hydrogen). Whenever available, the latest insights from the respective SCCERs are used (Marcucci et al., 2021b, Chapter 3). This was especially the case for the SCCER Biomass for Swiss Energy Future (SCCER-BIOSWEET) on biomass resources, as well as SCCER-SoE for hydropower and domestic CO_2 storage potentials.

Technologies: The assumptions of costs and efficiencies for key energy supply and demand technologies have been also harmonized. The main sources used are Bauer et al. (2019) and Bauer et al. (2017) for electricity generation technologies, Christensen (2020) for electrolysis, IEA (2019) for hydrogen production technologies, Radov et al. (2009) for end-use boilers and heat pumps, and the SCCER Efficient Technologies and Systems for Mobility (SCCER Mobility) for the transport technologies (Sacchi et al., 2021). The characterization of the biomass-related technologies in the energy conversion sectors, as well as the identification of the various biomass conversion routes considered in the context of JASM, are based on the collaboration with the SCCER-BIOSWEET as it is described in Guidati et al. (2021a).

Energy demands: We calculate the future energy service demands in the different end-use sectors with a reduced-form econometric model based on the harmonized drivers (Panos et al., 2021; Marcucci et al., 2021a):

- Space heat demand in the residential sector is related to the future energy reference area (ERA) that we estimated using population as the main driver. To calculate the ERA, we project the evolution of the building stock until 2060 by building type and age group following a building stock model. We then determined the heating demand using the estimations from UNIGE regarding the specific heating demand per building type and age, as well as the new building standards (Marcucci et al., 2021b).
- Space heat demand in the industrial and commercial sectors is also related to ERA, which is assumed to be linked to GDP, GVA and production index.
- Warm water and electricity demand in the residential sector is linked to population, while it follows the development of GDP, GVA and production index for industrial and commercial sectors.
- Process heat demand in industry is linked to economic development (GDP or GVA) and to physical output (i.e. production index).
- Finally, the future demand of transport (person- and ton-kilometer) is based on the Transport Outlook 2040 (ARE, 2016). We used the historical data from the BFS (2019b), BFS (2019c), and BFS (2019a) and the ARE (2016) growth rates of passenger demand per capita and freight demand per GDP. We then determined the demands using the JASM reference, high, and low variants of population and GDP. For the projections after 2040, we assumed a decreasing growth rate in the demand per capita and the demand per GDP for the passenger and freight demand, respectively.

2 JASM Scenario Definition

The JASM scenarios are defined along dimensions on which citizens and policymakers can exert influence, including climate policy, technology development and market integration. Studying a large variety of scenarios within our JASM framework allows us to distill those trends on technology use that are stable and, therefore, most likely part of a future energy system.

The STEM and SES models evaluate scenarios defined along three dimensions:

1. climate policy,
2. available technologies,
3. and market integration (with the EU or within Switzerland).

We selected these dimensions firstly because each directly influences energy-use or energy generation and secondly because each dimension is a lever on which citizens and policymakers *can exert influence* to achieve net-zero emissions in Switzerland. As mentioned in Section 1.5, we considered other external drivers, that *can not be influenced* – population and GDP, global climate change, and technology characteristics – in combination with these three dimensions.

As explained in Section 1.3, the energy system models are very different in structure and scope. Therefore, the translation of these scenario dimensions into concrete inputs is very model-specific, and explained in the different reports (Panos et al., 2021; Li et al., 2020; Marcucci et al., 2021a; Guidati et al., 2021b).

2.1 Climate Policy Dimension

In the climate policy dimension, we explored climate change mitigation targets, ranging from existing policies to the more ambitious net-zero CO_2 targets established by the Swiss Government. In 2015, Switzerland announced a long-term target of reducing GHGs by 70–85 % in 2050 compared to 1990 levels (Swiss Federal Council, 2015). Later, in August 2019, the Federal Council decided that Switzerland should reduce its GHG emissions to net-zero by 2050 (Swiss Federal Council, 2019), and an updated NDC (Nationally Determined Contribution) was submitted on 9 December 2020 to the United Nations (UN). In both cases, the target states that part of the reduction can be achieved by measures abroad.

We therefore considered three climate policy trajectories/targets:

1. Business as Usual (BAU)
2. Energy Policy (EPOL)
3. Climate Policy (CLI)

In BAU, we assume that all policies in place today will continue are their current stringency. In EPOL, we adopt the multiple objectives and measures of the Swiss Energy Strategy 2050 without a specific CO_2 target. Applied to the JASM framework, the EPOL scenario is exploratory and BAU is used to compare and benchmark the developments and to showcase upcoming challenges in long-term scenarios related to the energy system transition. Both BAU and EPOL are analyzed by STEM only.

The last climate policy in our JASM scenarios is the ambitious objective of reaching net-zero emissions ("CLI"). As explained in Section 1.1, unavoidable emissions in agriculture and industry require either a compensation outside Switzerland or the net removal of CO_2 from the atmosphere within the energy system. CLI was analyzed as a normative scenarios by STEM and SES-EPFL with a target of 0 and -6 Mt_{CO_2}/a inside the energy system, respectively, whereas SES-ETH used a sweep of CO_2 targets from +20 Mt_{CO_2}/a to the lowest value that can be achieved for the given assumptions.

2.2 Technology Dimension

Along this dimension, we assume different states of technology availability due to both technology development and public acceptance. Starting from a state in line with current technology availability (conservative) to a final state that assumes accelerated technology development, increased social acceptance, and greater infrastructure investments (progressive).

At the conservative starting point, we assume current technologies are available at currently estimated potentials and costs but that no significant changes to existing infrastructure or expanded public acceptance occur. In contrast, in the final progressive option, we include a larger set of technologies available in Switzerland at competitive prices due to technological breakthroughs and or increased acceptance.

2.3 Market Integration Dimension

Integrating into the European energy market is currently a topic of intense debate for consumers, policymakers, and market actors. The level of integration that Switzerland decides on will have important implications for energy prices and "energy independence".

In our scenarios, *moderate* integration mirrors the current situation: balancing electricity imports and exports during the year without an electricity agreement and importing fossil fuels with limited access to international markets for biofuels, synthetic e-fuels, hydrogen, or captured carbon. *High* integration assumes that there is an electricity agreement between Switzerland and the EU (as a result, the transmission capacity can be fully used), and an international market of biofuels, hydrogen, and captured carbon.

We model this dimension by changing the net transfer capacities and imports prices of electricity, as well as of other imported energy carriers. The STEM model is able to model consumers in great detail, thus, for STEM, this dimension also models "internal" integration within Switzerland. That is, prosumers participating in energy sales, both residential and commercial, forming also local energy markets. Thus, STEM can estimate the influence of these more progressive market developments that influence market integration of renewables, distributed generation, and sector coupling.

2.4 Scenario Variants and Synthesis

Each energy system model generated extra scenario variants to better work out the effects of certain key parameters on the resulting mix of technologies. These are described in detail in the respective reports and in Section 4.

Based on the individual model results, we identified the trends that are common to all three models. This comparison allowed us to identify technologies that are very likely part of the future mix and the ones that most likely will not play a role (see Section 5). Based on these insights we are able to formulate specific recommendations for policy measures and actions today; and to define the market drivers and the engineering and technical changes necessary to integrate technologies together to transform the energy system while achieving climate commitments.

3 Sectoral Models in JASM: Key Results and Inputs to the JASM Framework

Full energy system models have a representation of the whole energy system, and are naturally limited in their capabilities to model the specific sectoral details. On the contrary, sectoral models focus on certain key aspects but do not include linkages with the rest of the energy sector. In JASM, we soft-linked sectoral and energy-system models. In this section we present selected outputs that are further used in the energy-system models.

Climate change will impact the future hydropower generation heating and cooling demand. We base this assessment on the latest Swiss climate scenarios which were generated for the Representative Concentration Pathways RCP 2.6, 4.5 and 8.5 (CH2018, 2018).

3.1 Impact of Climate Change on Hydropower Generation

To determine the effect of climate change on the inflow to hydropower plants, we used discharge data from hydrologic modelling and passed it to the Swissmod model of UNIBAS (Schlecht and Weigt, 2014/04), which represents 96 % of Swiss hydropower stations. The hydrology dataset was generated by the hydrologic precipitation-runoff-evapotranspiration model PREVAH (Viviroli et al., 2009). It includes data from 39 climate model chains and comes at a 500 m x 500 m spatial resolution (Brunner et al., 2019).

To calculate inflows to hydropower stations, we first mapped the raster data to the Federal Office for the Environment (FOEN)'s catchment area GIS dataset. As a second step, we used the Swissmod GIS database of catchment areas to map inflow to individual hydropower cascades. Subsequently, we calculated inflows based on historical production patterns and calibrated historical annual inflows to match expected total yearly hydropower production of individual hydropower stations. Savelsberg et al. (2018) describes the data processing approach in more detail.

The resulting monthly inflow patterns are visualized in Figure 2 in energy units (available at https://data.sccer-jasm.ch/climate_hydro_inflows/). They represent the sum of inflows to run-of-river power plants and to storage lakes. The latter is turned into actual production by the regulated hydro power plants. Especially in the RCP 8.5 scenario, clear trends can be observed, with a decline of total inflow but also a shift from summer to winter. The RCP 2.6 and 4.5 scenarios show similar changes, yet to a smaller extent. These monthly patterns are directly used by the energy system models with the RCP scenario as a parameter of an external driver.

3.2 Effect of Climate Change on Heating and Cooling Demand

To determine the impact of the climate on the heating demand we used the simple but widely known approach of Heating Degree Days (HDD), using the most common definition HDD 20/12. For every day at which the average temperature is below the heating limit T_l = 12 °C we computed the difference of that temperature to an assumed building interior temperature T_i = 20 °C. Similarly, we determined the effect on the cooling demand by considering the changes of cooling degree days (CDD), which are the number of degrees that a day's average temperature is above a certain threshold (T_{max} = 18.3 °C).

Berger and Worlitschek (2019) calculated the future HDDs and CDDs for the three aforementioned climate scenarios (CH2018, 2018) using a GIS-based approach combining the spatial distribution of temperature (and therefore HDDs) and population. Figure 3 presents the median and the first and third quartiles of the HDD (available at https://data.sccer-jasm.ch/climate-data/). All full energy system models in JASM considered the impact of changing HDD on the heating demand, whereas only STEM modelled also the impact on cooling demand.

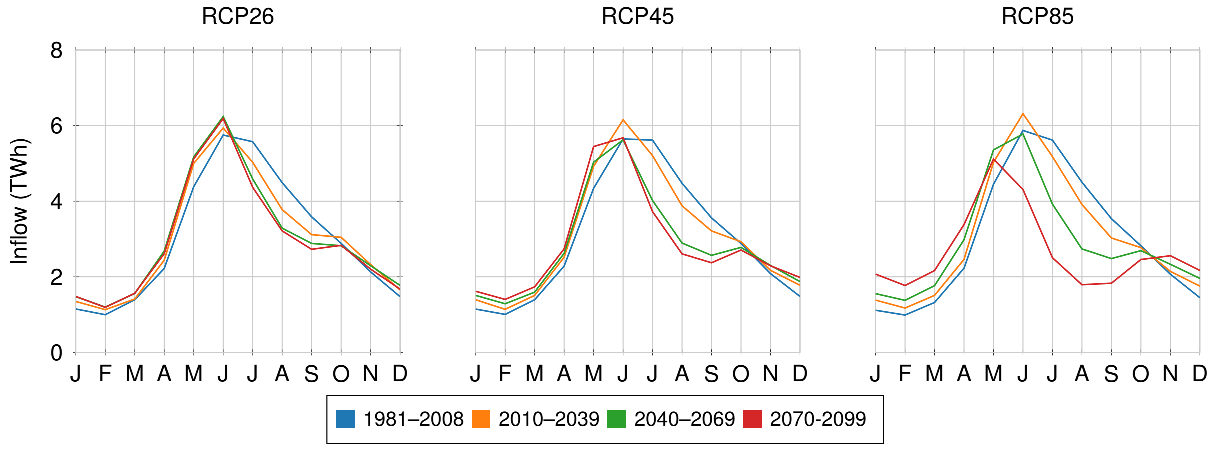


Figure 2: *Inflows to hydropower plants (run-of-river and storage lakes) under different RCPs and climatic periods.*

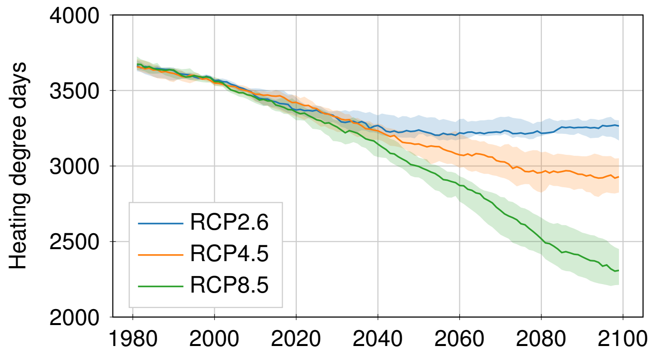


Figure 3: *Population weighted heating degree days in RCP 8.5, RCP 4.5 and RCP 2.6.*

3.3 Hourly Load Curves

Our energy system models have as an input the hourly demand series for energy services (in the residential, commercial, industrial and transport sectors). In our JASM framework, EMPA, the UNIGE, and HSR Rapperswil (Yilmaz et al., 2020) estimated these hourly profiles for different sectors and weather conditions. UNIGE collaborated with the local utility company Service Industriels de Genève (SIG) and developed the ElectroWhat platform that decomposes the yearly electricity consumption of every Swiss municipality into estimated load curves per activity and per electric appliance. EMPA used different simulations with the CESAR model to calculate the hourly profiles for commercial and residential buildings for today's building stock and future buildings with different retrofitting levels. HSR Rapperswil estimated the load curves for the space heating demand of single and multi-family houses using the TRNSYS model.

3.4 Energy Efficiency in Buildings

The insulation level of walls, windows and other parts of the building envelope changes the energy efficiency of the building. For this reason, renovations are particularly important in the residential and commercial sectors.

Residential sector. Streicher et al. (2020a) determined a relationship between energy savings and investment costs for the residential building stock using two different models. First, Streicher et al. (2020b) used the SwissRes model to calculate the investment costs of the renovation packages for the 2016 building stock using three different approaches. The first approach (full) includes all investment costs (related and not-related to energy efficiency improvements). The second approach (depreciation) accounts for the costs of the energy efficiency improvements plus a residual value to each building element. The third approach (improvement) accounts only for the cost of energy ef-

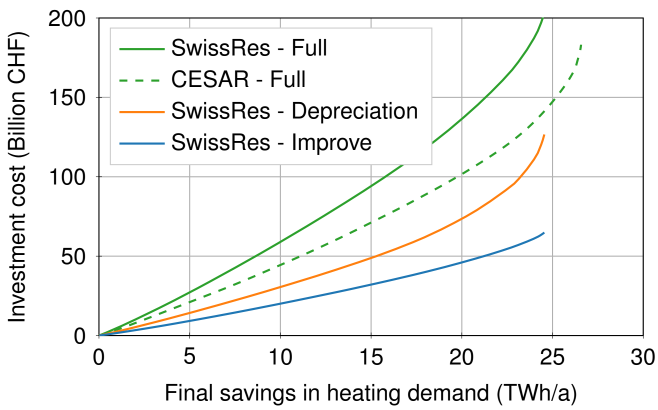


Figure 4: *Energy efficiency cost curves for the Swiss residential sector.*

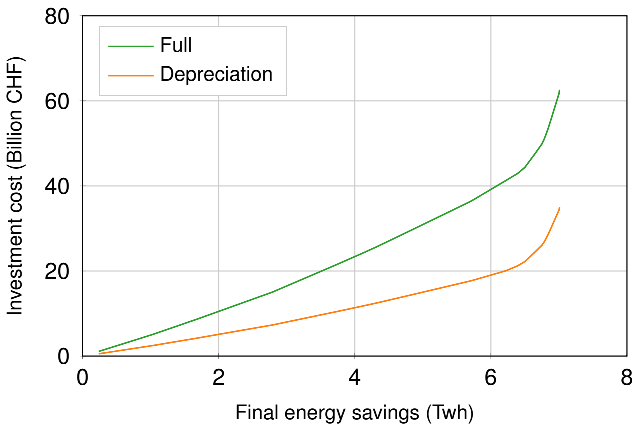


Figure 5: *Energy efficiency cost curve for the Swiss commercial sector.*

ficiency improvements. SwissRes looks at retrofitting packages as opposed to single measures as package retrofitting is an optimal way to realize efficiency gains and costs savings. That is, retrofit packages contain complementary measures. Second, EMPA used the CESAR model (Murray et al., 2020) to calculate annual heating energy savings and the investment costs associated with different retrofit scenarios for a set of residential building archetypes in Switzerland.

Figure 4 compares the resulting energy efficiency investment curves for the CESAR model and the scenarios of the SwissRes simulations (available at https://data.sccer-jasm.ch/energy-efficiency-residential-swissres/ and https://data.sccer-jasm.ch/retrofit-savings-cesar/). The costs with the CESAR model correspond to the Full cost approach of the calculation with the SwissRes model. Both models find similar total saving potentials of around 25 TWh for the current residential building stock with investment costs of around 100–200 Billion CHF, depending on the method of economic evaluation. Note, that the effect of building retrofits on the future *cooling* demand was not considered.

Commercial sector. For the commercial sector, the CESAR model was used to calculate the saving potentials and the corresponding investment costs for hospitals, offices, schools and shops including nine archetypes for each building type (Streicher et al., 2020a). The buildings covered by these archetypes account for 66 % of the total ERA in 2013, the remaining ERA corresponds to restaurants, hotels, agriculture buildings, transport buildings and other commercial buildings. To get the energy efficiency curve for the whole commercial sector we first upscaled, for each building type, the estimation from the nine archetypes to the full building stock. Second, we assumed that the missing building types have savings potentials per area (in kWh/m^2) and investment costs per energy saved (in CHF/kWh) that correspond to the average of the rest of the buildings. Finally, we added the temporarily used buildings assuming a distribution into age classes that corresponds to that in the residential sector. Figure 5 depicts the energy efficiency curve (available at https://data.sccer-jasm.ch/retrofit-savings-cesar/). The total saving for today's commercial sector are around 7 TWh with total investment costs of 50–60 Billion CHF.

The results of both the CESAR and the SwissRes model show that an energy retrofit of the buildings in both the residential and the commercial sectors could achieve a reduction of roughly 50 % (32 TWh/a) of the total final energy demand of space heating. Note, that this saving assumes constant climate, reductions due to climate change are considered separately in the models (see Section 3.2).

3.5 Energy Efficiency in Industry

Zuberi et al. (2020) (based on Zuberi and Patel (2019), Zuberi et al. (2018), Zuberi et al. (2017), Zuberi and Patel (2017), Bhadbhade et al. (2019), and Bhadbhade and Patel (2020)) calculated energy potential savings and costs for various industrial sectors in Switzerland. The estimation is done using techno-economic data on energy efficiency measures from multiple sources which mainly include the Energy Agency of the Swiss Private Sector (EnAW), the ProKilowatt scheme by Swiss Federal Office of Energy (SFOE) and individual companies. The analysis considered the four most energy consuming sectors and systems, i.e. chemicals and pharmaceuticals, food and beverages, cement, metals, and process heat and electric motor driven systems. Process heating and electric motor systems correspond to approx. 50 % and 30 % of the Swiss industrial final energy demand. Figure 6 presents the energy efficiency curves for heat and electricity (available at https://data.sccer-jasm.ch/energy-efficiency-industry/).

3.6 Photovoltaics Hosting Capacity of Distribution Grids

Our scenario results indicate that photovoltaics (PV) is indeed a crucial element of the future electricity generation mix (see Section 4). However, the majority of small- and commercial-scale PV plants will likely

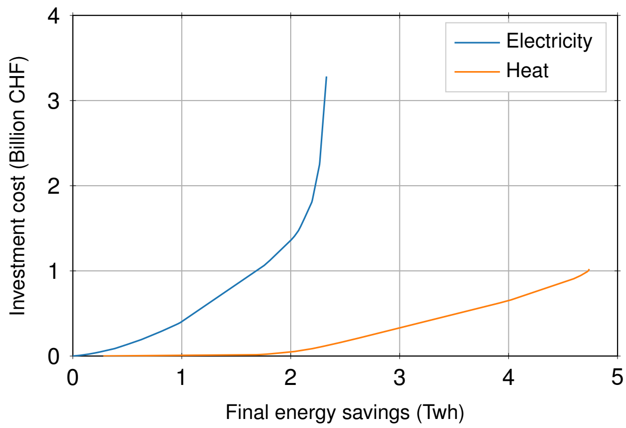


Figure 6: *Energy efficiency cost curve for the Swiss industry.*

be connected to electrical distribution grids, which were not designed to host a significant power generation. Modeling the existing electrical distribution infrastructure's technical constraints is, therefore, critical to ensure the feasibility and economic viability of the overall net-zero scenarios. One dedicated sectoral model was developed at EPFL to address this issue (Gupta et al., 2020).

Estimating the PV generation hosting capacity of existing electrical distribution grids requires the information on network topologies and line parameters of the distribution systems for Switzerland. As this data is not publicly available, we first inferred a country-wide model of the medium-voltage distribution networks based on spatially distributed information of the electrical demand, leveraging information freely available from the Federal Office of Topography (swisstopo), land-use constraints, location of the extra-high-voltage nodes, and distributed solar irradiance potential.

We then estimated the PV generation hosting capacity for all Switzerland with a state-of-the-art and computationally tractable method based on a linearized optimal power flow. We ultimately investigated the economically optimal deployment of PV power plants across Switzerland, including the placement and sizing of battery energy storage systems to increase the generation hosting capacity of those distribution grids with significant solar radiation levels.

Thanks to the developed grid model, we could estimate that up to 15 GW of PV could be installed in the existing grid infrastructure without the need of significant upgrades of the electrical distribution grid. We also computed the amount of energy storage required to increase the PV generation capacity beyond this hosting capacity limit.

Figure 7 shows the energy capacity and power rating requirements of battery storage as a function of the installed PV generation capacity. The need for storage increases approximately linearly beyond 15 GW. Assuming a final target in the order of 25 GW, which is found in our scenario results, Switzerland would need some 50–60 GWh of installed battery capacity. At prices of approx. 400 CHF/kWh this would result in extra investments of 20–25 BCHF, which is a similar range as the investment costs of the PV generation itself.

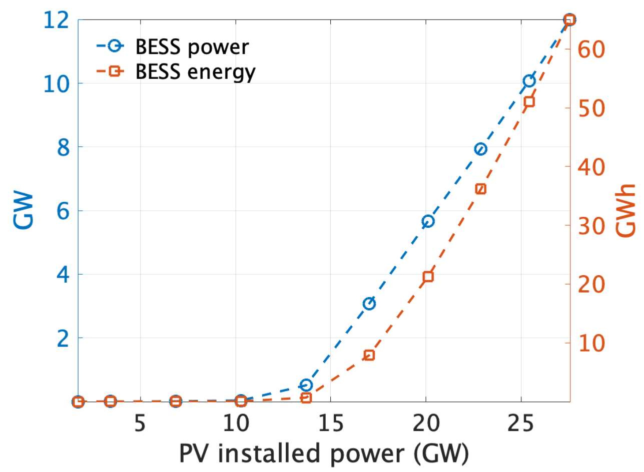


Figure 7: *Battery Energy Storage System (BESS) power rating and energy capacity for different levels of installed PV generation capacity.*

4 Scenario Results from Energy System Models

The full scenario models STEM, SES-EPFL and SES-ETH have different characteristics that lead to interesting and complementary results for the design of the energy system in a net-zero emissions world. STEM has the capability of analyzing the transition pathways while the SES models focus on the impact of uncertainty on the design of the future energy systems. We also show results of a specific case study for the city of Baden. In the following Section 5 we synthesize these results into common takeaways for the realization of the net-zero emissions target.

4.1 STEM - Optimal Transition Pathways

The Swiss TIMES Energy systems Model (STEM) (Panos et al., 2019; Kannan and Turton, 2014) has a long-term horizon (2010–2100) with 288 intra-annual operating hours (four seasons and three typical days per season with 24 h resolution). It covers the whole Swiss energy system with a broad suite of energy and emissions commodities, technologies and infrastructure, from resource supply to energy conversion and usage in 17 energy demand (sub-) sectors. STEM aims to supply energy services at minimum overall system cost (more accurately at a minimum loss of surplus) by simultaneously making equipment investment and operating, primary energy supply, and energy trade decisions (Figure 8).

Three core scenarios are examined reflecting different transition pathways regarding energy and climate policies. All scenarios implement a gradual phase out of nuclear power plants, by considering a lifetime of 60 years (with the exception of Mühleberg). The Baseline (BAU) scenario assumes a continuation of existing trends in energy consumption and supply, as well as in the technology developments for energy production, distribution and use. It does not enforce specific long-term targets regarding renewables' deployment, energy efficiency measures or climate change mitigation. BAU is primarily used to compare and benchmark the developments and showcase upcoming challenges in the long-term scenarios related to the energy system transition.

The Energy Policy (EPOL) scenario considers the measures and targets of the Swiss Energy Strategy (BFE, 2018). It implements both the targets on renewable energy deployment and energy efficiency, including the indicative target in electricity consumption per capita, as defined in the Swiss Energy Strategy. While EPOL does not impose a specific target in reducing emissions, it implements the new energy act on mobility. EPOL is an explorative scenario, evaluating the level of emissions abatement achieved primarily via the energy efficiency measures described in the Swiss energy strategy.

The Net-Zero (CLI) scenario aims at achieving net-zero emissions in the energy system and industrial processes, i.e. within the scope of STEM[1]. Considering emissions outside the energy system from agriculture and waste treatment (other than fuel combustion), the resulting CO_2 emission level within the CLI scenario will still be in the order of +5 to +6 Mt_{CO_2}/a. The CLI scenario implements emissions standards for buildings and vehicles, and it assumes the strengthening of the Swiss and EU emission trading schemes.

Besides the CLI core scenario, variants addressing key dimensions of the energy transition, such as resource availability, technical progress, and market integration, are also assessed. The ANTI variant assumes a fragmented international climate policy, slow technical progress, weak integration of energy markets, and low exploitation of domestic renewable energy. The SECUR variant builds on ANTI, but it assumes that the Swiss society is keener in fully exploiting the sustainable potential of domestic renewable resources, to minimize the import dependency.The MARKETS variant

[1] Referring to the GHG inventory of Switzerland submitted to UNFCCC, the emissions within the scope of STEM are from 1A to 5A (i.e. emissions from fuel combustion in energy sector, manufacturing, transport, services, agriculture and residential) and 2 (i.e. non-energy related emissions from industrial processes including mineral industry, chemical industry, metal industry, non-energy products from fuels and solvent use and other manufacturing), see Sheet "Summary1.As1" in Switzerland's national GHG inventory reports which can be downloaded from the Federal Office for the Environment (FOEN).

assumes high access to domestic renewable energy sources as in SECUR, and it also considers a higher integration of the Swiss and international markets, beyond the levels of CLI. The INNOV variant builds on MARKETS, and it also assumes globally coordinated R&D spending to reduce the costs of low-carbon technologies. The CLI100 variant does not implement the efficiency and emissions standards/targets in the demand sectors of CLI beyond 2030.

Finally, a variant of the EPOL scenario is also considered in the analysis that enables higher electrification of the demand by not implementing the reduction in the electricity per capita indicated in the Swiss Energy Strategy (variant EPOL-E).

Figure 9 highlights important aspects of the transition pathway towards net-zero within the energy system with a focus on the CLI scenario.The full STEM report can be found in (Panos et al., 2021). The most important insights from STEM modelling are:

Achieving the Swiss energy and climate goals would require scaling up clean energy technologies. The ambition to reach the net-zero CO_2 emissions objective by 2050 requires a radical transformation of the way energy is supplied, transformed and used. It is necessary to deploy solar PV, electric and hydrogen cars, heat pumps, and energy savings measures on a far greater scale and more rapidly than today.

In electricity supply, the installed capacity of solar PV needs to double every decade from now to 2050. The electricity from solar PV is ten times higher in 2050 than today. The contribution of non-hydro renewable energy electricity in total supply increases to 45 % in 2050, with much of this expansion occurring in the post-2040 period.

The private car fleet will need to be mostly based on electric drive trains by 2050, which implies that one in every three new car registrations must be electric already by 2030s. In CLI, the period from now until 2050 is divided into three principal stages:

a) the period until 2030 is characterized by a transition with many options competing
b) the period 2030–2040 sees a rapid introduction of electric vehicles
c) the period 2040–2050 in which fuel cell cars gain share in the market

In the public and freight road transport, the transition is characterized by strong hybridization until 2040, while afterwards battery and fuel cell drivetrains become increasingly competitive and start gaining market share. The fuel mix in transport shifts away from fossil fuels towards electricity, hydrogen, and zero-carbon fuels (mostly imported bioliquids or synthetic e-fuels produced with renewable electricity and CO_2 capture).

The deployment of heat pumps needs to accelerate in both services and residential sectors so that, by

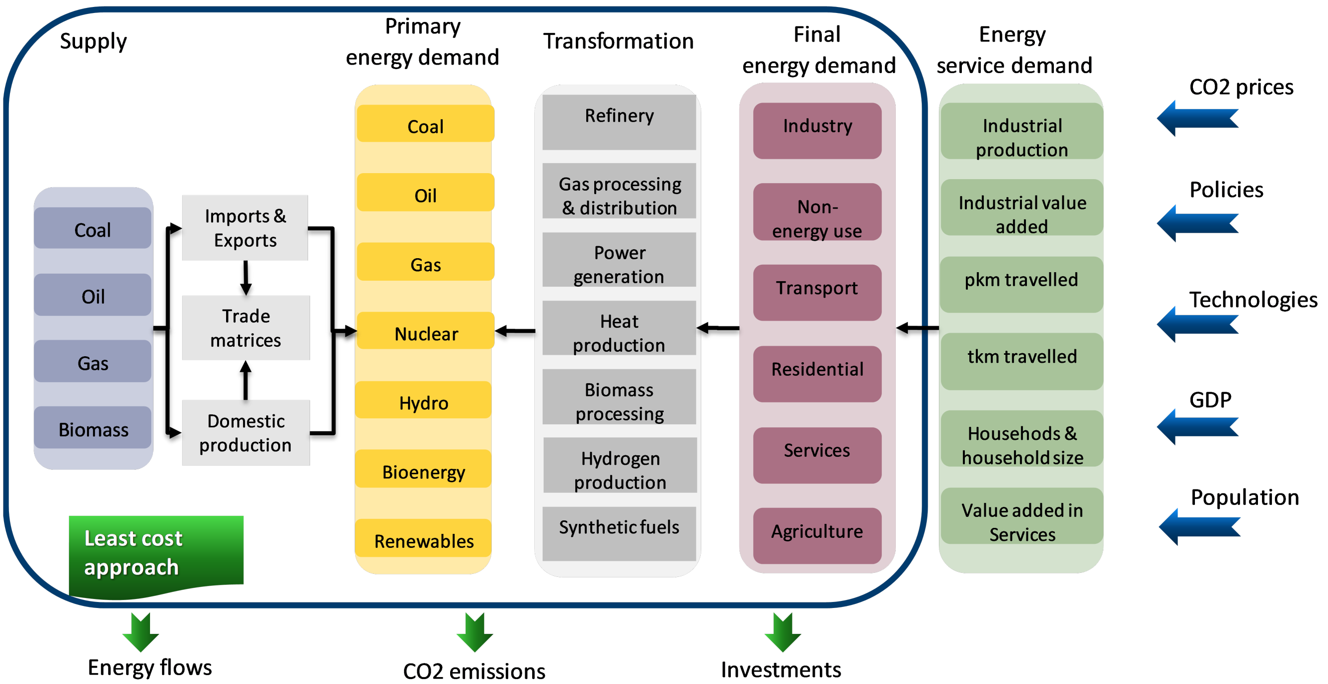
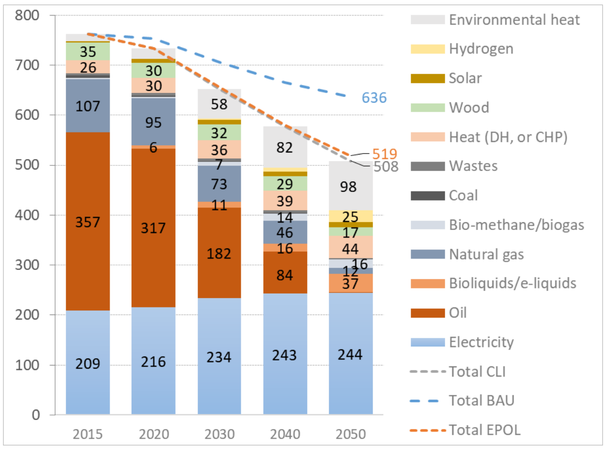
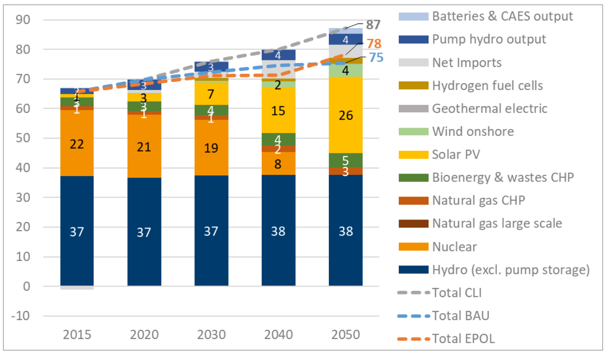


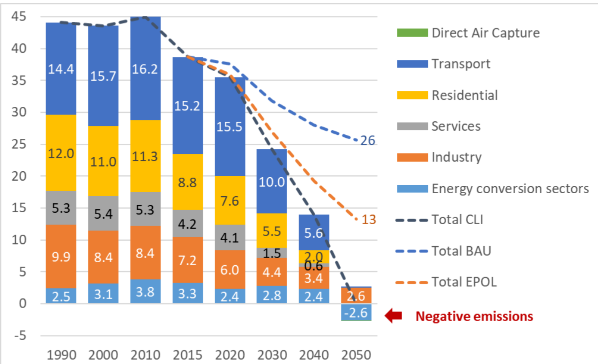
Figure 8: *Overview of the STEM model structure and concept.*



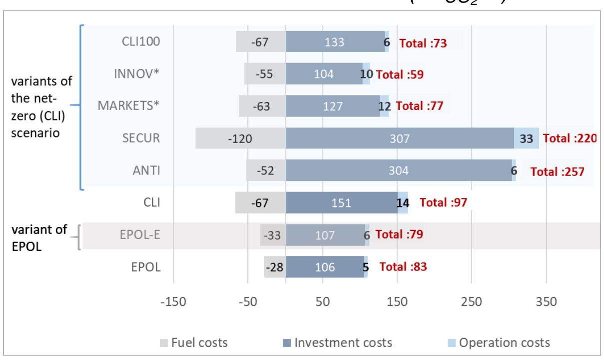
(a) *Total final energy consumption by fuel in CLI (excl. international aviation and CHPs), PJ/a.*



(b) *Electricity supply mix in the CLI scenario, TWh/a.*



(c) *CO_2 emissions from fuel combustion and industrial processes – on-site CHPs are accounted to the emissions from the end-use sectors (Mt_{CO_2}/a).*



(d) *Cumulative direct policy costs 2020–2050, discounted at 2.5 % social discount rate, $BCHF_{2010}$.*

Figure 9: *STEM main results.*

2050, heat pumps would cover close to three quarters of the space and water heating demand in buildings. It would also be necessary to reap efficiency gains by rolling out energy-saving measures through accelerated renovation the deployment of which needs to start from now and increase in the post-2030 period.

Electricity – a key energy carrier in reaching net-zero emissions. The total electricity consumption in the end-use sectors increases by 11 TWh in 2050 compared to 2019. There is accelerated electrification of the demand until 2030, driven by heat pumps and electric vehicles. However, in the post-2030 period transport is the main driver of the continuing electrification of the demand, as efficiency gains and energy conservation measures lead to a plateauing of electricity consumption in stationary sectors. Electrification and efficiency improvements in demand enable a reduction of the total final energy consumption per capita by 55 % in 2050 compared to 2000 levels, slightly higher than the long-term target of the Swiss Energy Strategy. It should be noted that the overall electricity supply needs to increase by around 20 TWh between 2019 and 2050, as a significant amount of electricity is needed also to produce hydrogen after 2040.

Electrification alone cannot decarbonize the entire energy system. Hydrogen penetrates the industry and mobility sectors for applications where the direct use of electricity is challenging or associated with very high costs. In 2050 more than 10 TWh of hydrogen are used, directly in fuel cells CHPs, fuel cell vehicles and hydrogen boilers, or indirectly via conversion of hydrogen to synthetic fuels. The uptake of hydrogen mainly accelerates in the post-2030 period. Besides hydrogen, imported biofuels and synthetic e-fuels of about 10 TWh are needed in 2050, which are used in the hard-to-electrify sectors of long-distance public and freight road transport and heavy industry.

CO_2 capture and bioenergy play an important role. Achieving the net-zero goal in a cost-efficient way would require capturing about 8.6 Mt CO_2 in 2050 from the energy system and industrial processes. About half of the captured emissions are from negative emissions technologies such as bioenergy with CO_2 capture and direct air capture. Bioenergy conversion with CO_2 capture can become vital not only for removing CO_2 from the atmosphere but also for producing hydrogen, which is also directly used to replace fossil fuels. Failing to harvest the remaining exploitable sustainable potential of bioenergy would entail high climate change mitigation costs. Moreover, given that storing captured CO_2 in Switzerland is a major challenge, the access to international CO_2 transport and storage infrastructure would be essential to avoid a drastic increase in mitigation costs.

Achieving the net-zero goal is technically feasible but requires coordinated efforts across all sectors. In 2050, the remaining emissions are in industry and relate to processes that need gaseous and solid (such as waste) fuels. The penetration of alternative vehicles, heat pumps and efficiency measures via renovation to fully decarbonize transport and buildings implies that more than two-thirds of the emissions reduction required to achieve the net-zero emissions goal stem from technologies that are already commercially available or under demonstration. However, to scale-up their deployment, energy companies and industry would need clear long-term strategies. Transforming the entire energy system will require progress across a wide range of technologies and action across all sectors, not just electricity. Long-term policy targets need to be backed up by detailed, clean energy technology strategies that involve measures tailored to local infrastructure and technology integration needs, and that achieve high levels of social acceptance of the new technologies.

Cost-efficient deep decarbonization needs all the options to be on the table, including access to international energy markets. The cost of the transition of the Swiss energy system to net-zero emissions in 2050 depends on the resource availability, social acceptance, technology progress, and the level of integration of local, national and international markets. It is also affected by the mitigation level already achieved in the reference scenario, against which the policy cost is calculated. The developments in the aforementioned factors reveal a large cost range, which indicates the uncertainty range of the abatement effort.

The lowest mitigation cost occurs when decarbonization can be achieved based on the availability of all possible least-cost mitigation options, and if research and innovation succeed in improving the performance and reducing the costs of low-carbon technologies. Under favourable conditions, the complete decarbonization of the energy system requires cumulative system costs of 59 billion CHF_{2010} from 2020 to 2050 discounted at a 2.5 % social discount rate (or, 97 billion CHF_{2010} undiscounted).

The highest mitigation costs occur when the transition to a low-carbon economy faces fragmented national and international policies, low level of cooperation and market integration, a low exploitation rate of renewable resources, slow technical progress and limited social acceptance. In such an extreme case, the cost can be as high as 257 billion CHF_{2010} from 2020 to 2050 discounted at 2.5 % discount rate (426 billion CHF_{2010} undiscounted).

The core net-zero scenario evaluated in this study (CLI scenario) shows cumulative costs of 97 billion CHF_{2010} over the period of 2020–2050, discounted at 2.5 %, or 163 billion CHF_{2010} undiscounted. The transport sector has the lion's share in the incremental investment needs in CLI, with an additional cumulative discounted investment expenditure of 46 billion CHF_{2010} when compared to BAU, due to the shift to alternative drivetrains. In terms of average per capita cost per year, the policy cost in CLI translates to 330 CHF_{2010}/a discounted, or 540 CHF_{2010}/a undiscounted from now until 2050. It should be noted that the per capita costs are averaged over the investigated time horizon until 2050, which is characterized by a fundamental transformation of the energy system and new technology and fuel mixes. The associated annual policy costs increase exponentially over the projection period, meaning that by 2050 we have built a more expensive energy system, which will require endured investments and expenditures for low carbon energy supply and demand also beyond 2050.

The transition to net-zero entails both challenges and opportunities in all sectors of the Swiss energy system. The analysis of the core scenarios and their variants shows that if energy savings and key technologies for the transition, access to zero-carbon energy carriers and development of the corresponding transport and distribution infrastructure fail to scale up, then the feasibility of reaching the net-zero target would be challenged, or the target would only be achieved at higher costs. The above affects each sector of the energy system.

In the ***building sector***, the rate of renovation and deployment of new efficient heating and electrical equipment needs to be significantly increased. These building technologies need to support future full renewable energy supply through demand side management (DSM). Still, their current payback times and the "split incentives" between landlords and tenants make investments financially unattractive. To reap the benefits of the transition, targeted policies would be needed to lift barriers related to financing or behaviour along with promoting the use of cutting edge IT solutions to enable smart use of energy.

In ***industry***, the required emission reduction are linked not only to the use of Best Available Technologies, but also to the development of low-carbon solutions, including electrification, use of zero-carbon fuels, CO_2 capture, and material efficiency. To facilitate the transition without jeopardising the competitiveness of the Swiss industry, roadmaps should be developed in combination with new market designs that encourage consumption of low-carbon intensity industrial products. The timely replacement of ageing infrastructure and assets with alternatives that are more compatible with the decarbonization targets can offer an opportunity to a cost-effective transition if investors receive suitable long-term price signals from markets and policies.

In the ***mobility sector***, the growing momentum for electric vehicles needs to be amplified, until other zero-carbon options, e.g. hydrogen fuel cells, become available on a larger scale towards mid-century. Biofuels and synthetic e-fuels have the advantage in their direct use in conventional vehicles without altering the existing infrastructure. However, biofuels are associated with land use and food security concerns. E-fuels require substantial amounts of electricity for their production, while their life-cycle emissions depend on the source of carbon used. Therefore, the transport modes where biofuels and synthetic e-fuels would be deployed need to be carefully considered. Stronger integration of the mobility sector with the rest of the energy system is also essential. For instance, grid-to-vehicle and vehicle-to-grid schemes can turn vehicles into multi-purpose assets that generate cost savings for owners and provide flexibility to the energy system.

The domestic ***bioenergy*** potential needs to be unlocked, and the infrastructure for bioenergy distribution needs to be further developed. The demand for bioenergy in 2050 is twice today's levels, and it cannot be met by only using renewable waste, agricultural and wood residues. The exploitation of the sustainable potential of manure and forest wood would need to be intensified. To unlock scale effects in manure for biogas production, financial obstacles need to be overcome, and technical barriers to its collection need to be lifted. At the same time, the availability of wood largely depends on the intensity of forest wood management and a balance with non-energetic uses of forests needs also to be achieved.

Hydrogen produced from low-carbon sources gains growing importance in a climate-neutral Swiss economy in 2050. As such, strong climate policy is a prerequisite for hydrogen deployment. Besides, the future success and timing of a hydrogen economy are highly dependent on technological developments and targeted measures. The mid-term horizon until 2030/40 is crucial for the wider deployment of hydrogen in the long term. As investment cycles in the energy conversion sector run for about two to three decades and the time needed for new energy technologies to penetrate existing markets is long, stimulating commercial demand and supply of clean hydrogen requires various forms of support. During the transition phase of the hydrogen infrastructure development, policy support should prevent creating stranded assets and discourage investments in hydrogen production technologies that do not meet long-term environmental criteria.

The ***electricity supply*** shifts from demand-following to largely weather-driven production and faces the need for additional system *flexibility*. The electricity market needs to open and create active participation opportunities for centralised storage (including new solutions on Power-to-X, hydrogen and e-fuels), for flexible consumers (individual ones or those collectively offering their capacities through aggregators) with decentralised storages and smart demand technologies, and for electricity producers who can be integrated via peer-to-peer trading. The regulatory framework needed to support this major change in the electricity market structure will also require stronger and closer cooperation across Transmission and Distribution System Operators (TSO) than today.

The ***district heating and cooling*** network operators also have an essential role in the energy transition because district heating systems provide flexibility for integrating different renewable energy sources. By 2050 district heating systems largely rely on a range of low- and zero-carbon options such as solar, biomass, geothermal, and heat storages.

This implies a transformation of the network itself, building on smart integration of energy systems and prosumers' involvement. District heating networks would need to be embedded in an overall plan across multiple infrastructures (including electricity and gas grids) with coordination between local authorities and service providers, as well as alignment with other infrastructure developments.

Negative emission technologies are essential for the transition towards a net-zero CO_2 energy system in order to offset the remaining emissions that are most difficult to abate in transport, in industry and from waste management. If storing CO_2 in Switzerland is uncertain or limited, Switzerland would need to obtain access to infrastructures transporting CO_2 abroad, participate in establishing a consistent framework to account correctly for emission removals, and sign international agreements for delivery contracts.

Overall, ***an affordable transition to decarbonization*** is built around three main pillars. The first pillar is the exploitation of the remaining sustainable domestic renewable energy potential, including keeping hydro at least at the current level and securing access to the sustainable bioenergy potential to deliver negative emissions. The second pillar is the integration of energy markets, especially those involving the trading of new energy carriers such as hydrogen and synthetic fuels. The third pillar is technology innovation and R&D worldwide on low carbon technologies, to reduce their costs and improve the overall performance. The transition to a low carbon energy economy can be accelerated by technological progress and circular economy practices that reduce the cost of materials, renovation costs and costs of implementing energy conservation schemes.

4.2 System Adequacy Assessment

Transmission system adequacy is key for the functioning of the future energy system. The Swissmod model (Schlecht and Weigt, 2014/04) was used to calculate different adequacy indicators for some of the aforementioned scenarios analyzed by the STEM model (Schlecht and Weigt, 2020). For this purpose, PSI and UNIBAS soft-linked the two models by mapping technologies and translating the STEM results to the different intra-annual timescale used in Swissmod.

Our analysis shows that Switzerland is well equipped on the capacity side until 2040 and can successfully manage the critical short-term situations arising. Only very small loss of load can be observed in the CLI scenario for 2040, which considers already the larger demand due to electro-mobility and electrolysis. A detailed analysis shows that this is due to transmission grid constraints and likely in a range that could be managed by the TSO using short-term switching actions or by allowing temporary violations of the 20 % grid security margin that we consider in our model. The adequacy assessment highlights the importance of European developments and thereby the importance of both sufficient cross-border transmission capacities as well as an integration of the Swiss energy system into the European market and system structure. While the existing and projected transmission and generation capacities are large enough to ensure system adequacy, the ongoing negotiations about the electricity agreement between Switzerland and the European Union (which has impacts on Switzerland's electricity exchange possibilities with its neighbors) put the main focus of the Swiss system adequacy into the political dimension and not the physical energy dimension.

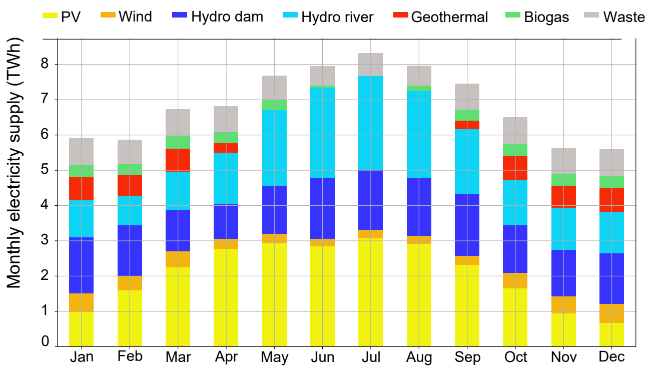


Figure 10: *Optimized monthly power generation in a -6 Mt_{CO_2}/a scenario.*

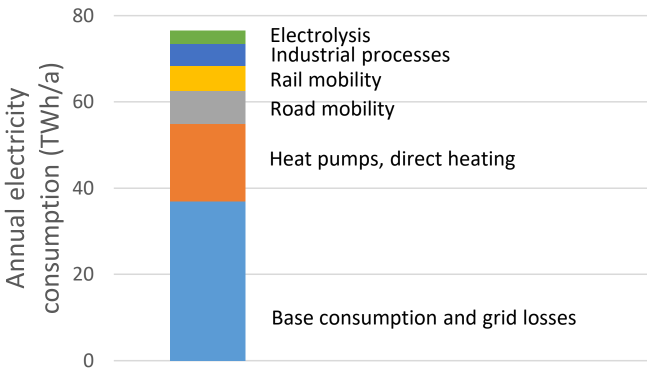


Figure 11: *Optimized power consumption in a -6 Mt_{CO_2}/a scenario.*

4.3 SES-EPFL - Optimal Technology Mix under Uncertainty

Swiss Energyscope (SES) was developed by IPESE at EPFL for exploring optimal investment and operation strategies of the Swiss energy system in long terms subjected to various techno-environmental constraints. The model is a snapshot of prospective scenarios with monthly time resolution, resulting in a good performance of the trade-off between modeling contents, which include all key areas in the energy system, and computational complexity. Apart from conventional analysis on the energy demand-supply covering electricity, heat and mobility, special attention was paid on the carbon flows contributing to modelling the circular economy in the context of increasing advocacy for CCUS, especially for BECCS. Typical chemicals/plastics are also considered in order to have a more holistic view on the whole system.

In this study, a normative scenario is defined aiming at realizing -6 Mt_{CO_2}/a emission autonomously in the energy system in order to compensate unavoidable emission in non-energetic sectors, particularly agriculture (Li et al., 2020). The model demonstrates that carbon neutrality is achievable with a quasi 100% penetration of renewables except 5–10 % from non-biogenic waste incineration, where domestic hydro, solar, wind and biogenic resources are fully exploited (see Figure 10). In total, 78 TWh/a electricity are produced where 37 TWh/a feeds the base load (including the grid losses), and the remaining are consumed within the energy system, predominantly by heat pumps and electric vehicles (see Figure 11).

Strong seasonality is witnessed in the power generation, which has to be balanced by around 11 TWh/a of seasonal storage, where hydro storage in form of the alpine reservoirs contributes the largest part, with hydrogen and synthetic natural gas storage as major backups (see Figure 12). Mobility is highly electrified with penetration rate around 90 %. In terms of heat demand, waste CHP plants contribute the most (55 %) to the process heat supply, and decentralized heat pumps account for 56 % for space heating and hot water supply.

Concerning the emissions, Figure 13 describes the carbon flows quantitatively for both biogenic and non-biogenic sources/sinks within the energy system and exchanges with atmosphere and the underground. From the optimization results, around 0.8 Mt_{CO_2}/a are used for generating synthetic fuels and plastics, where the latter serve as a carbon sink while the former circulate in the energy system. In total, 5 Mt_{CO_2}/a stem from **fossil** sources and 11 Mt_{CO_2}/a is **sequestrated** underground, leading to +6 Mt_{CO_2}/a **net bio-capture**, demonstrating how the -6 Mt_{CO_2}/a emission target is achieved.

Subsequently, we performed a Monte Carlo simulation on the energy efficiency improvements (building renovation, heat recovery and innovative process integration in industry, and mobility electrification), key technologies' potentials and importing prices of fuels respectively, leading to various uncertainty ranges for key technologies in the energy transition. Figure 14 shows the multiple solutions towards the negative carbon emission objective driven by efficiency uncertainties, with corresponding probability quantiles. The results illustrate that energy efficiency improvements would result in considerable savings in the heating demand, reflected by the large variation of utilization of heat pumps and geothermal.

Electrification is proved to be vital in realizing the carbon neutral objective. The system cost presents large fluctuation in different scenarios. Biomass is mainly used for green fuel generation across the solution space, despite some distinctions of specific configurations in different scenarios. Instead, PV, wind and hydro power generation are robust against uncertainties that are supposed to be developed in priority. From our results, around 11 Mt_{CO_2}/a needs to be sequestrated, which calls for logistics to be planned from now on. Biomass-based plants, waste incineration and cement are the core areas to deploy carbon capture technologies. Pilot projects are necessary to furthermore demonstrate the techno-economic feasibility of the solutions.

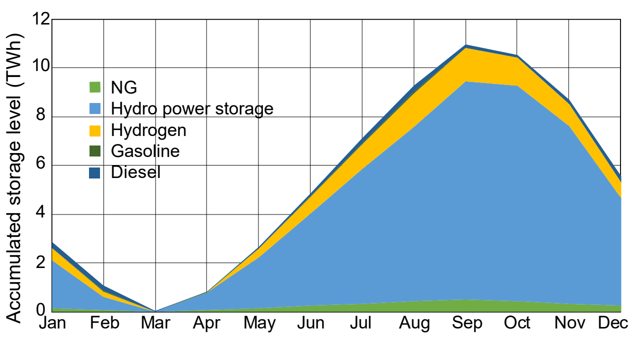


Figure 12: *Seasonal storage level.*

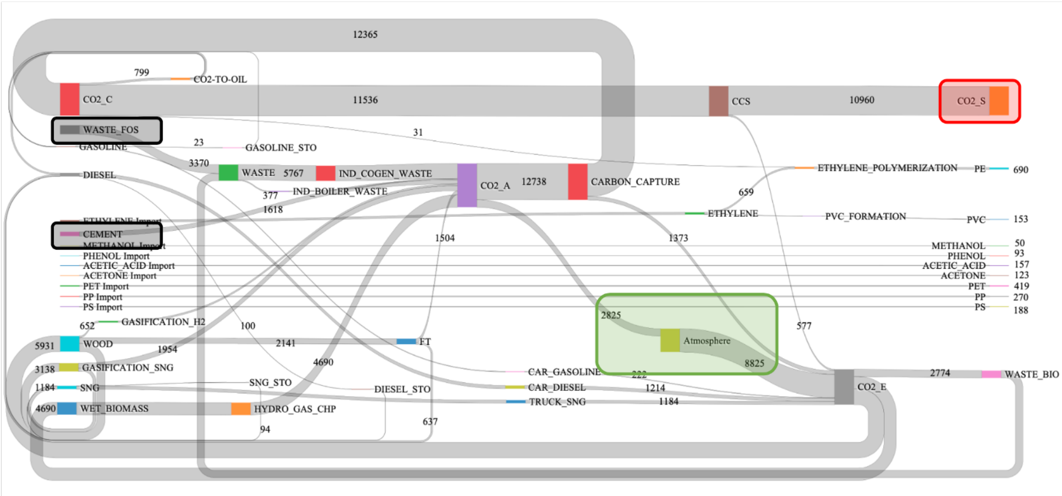


Figure 13: *Circular carbon flow (Mt_{CO_2}/a) in a complex energy system for achieving -6 Mt_{CO_2}/a.*

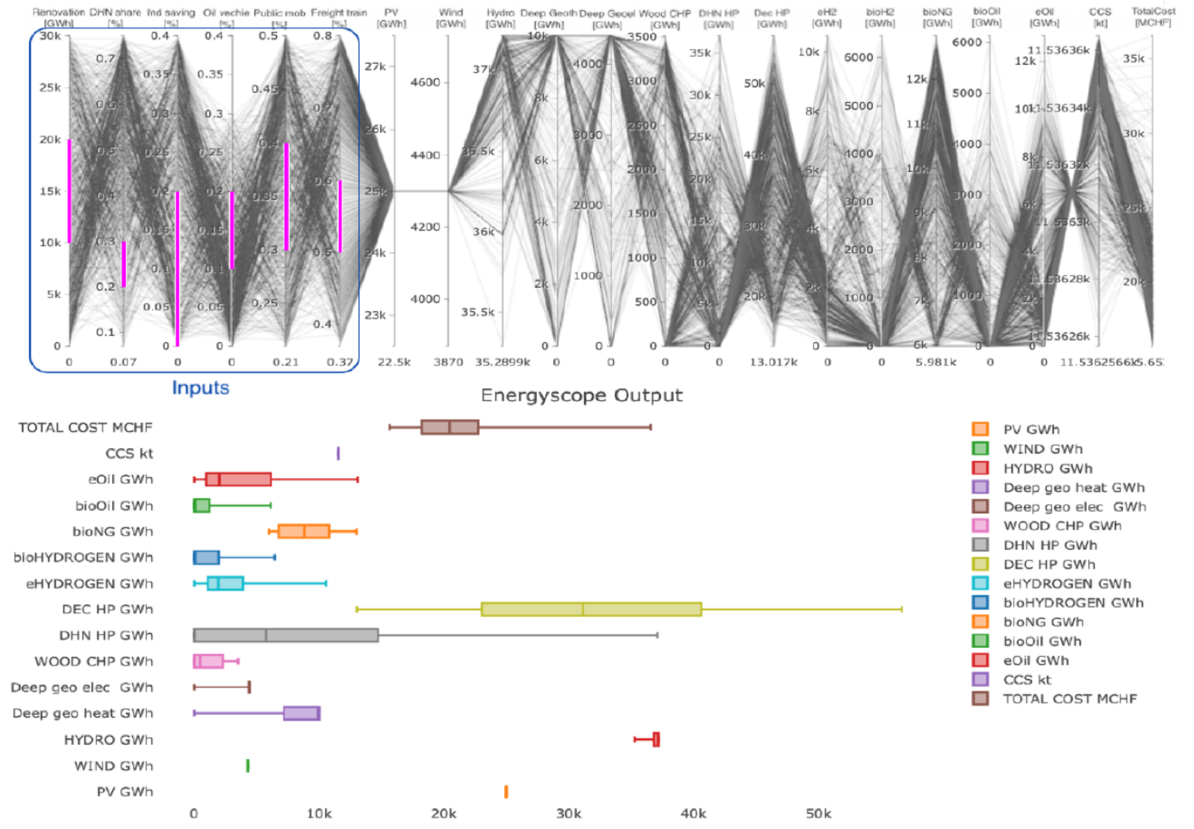


Figure 14: *Multiple-solutions towards carbon neutrality driven by the uncertainty of energy efficiencies.*

4.4 SES-ETH - Optimal Technology Mix under Uncertainty

The original Swiss Energyscope (SES) model (Moret, 2017) was further developed at ETH, by including a typical day approach with hourly resolution, a more detailed representation of residential and industrial heat consumption by defining a number of archetypes, and an explicit treatment of different CO_2 streams to better account for the effects of carbon storage (Marcucci et al., 2021a).

Most drivers that influence the future energy system are uncertain. In our analysis we consider two categories of uncertainty and treat them differently. The first relates to levers on which citizens and policymakers can exert influence: the attitude – conservative vs. progressive – towards the deployment of novel technologies (e.g. deep geothermal heat, new alpine hydropower plants) and the integration with an EU-wide CO_2 transport and storage infrastructure. We use these factors to define the dimensions of a few *discrete* scenario variants (see Table 1). The uncertainty on the Swiss climate policy is considered by simply sweeping through all possible CO_2 targets from +20 Mt_{CO_2}/a down to the lowest achievable level.

Table 1: *Discrete scenario variants of CLI in SES-ETH.*

Market integration	Technology development: Conservative	Technology development: Progressive
no CO_2 storage	Yesterday	Revolution
with CO_2 storage	Come together	Imagine

The second type of uncertainty includes factors that are not sensitive to domestic policies or individual behavior, including macro-economic drivers such as population and GDP, global climate change, technology costs, and the availability and costs of resources. We analyze this uncertainty with *continuous* probability distributions using a Monte Carlo simulation. With this approach we obtain probability distributions for all resulting characteristics of the energy system, e.g. the amount of photovoltaic electricity generation. These results reveal trends and inter-dependencies which are more informative than point-estimates alone: we can identify the developments in the energy system that are more or less fixed – that are common to all the scenario results – and those that vary significantly. These types of insights are essential to inform decision making, since they allow us to formulate robust recommendations for actions in the fields of research & development, pilot & demonstration and policy measures.

Figure 15 shows the probability distributions of the stored CO_2 emissions, the total electricity generation, and the generation with new renewables for the scenario variants against the energy-related carbon emissions. Results show the median (white dash), the interquartile range (colored box) and the minimum and maximum (the lines above and below the box). The range of the net-zero GHG emissions target (-4 to -8 Mt_{CO_2}/a) is marked in grey.

First, concerning carbon captured, we can see that the target range for net-zero emissions (from -4 to -8 Mt_{CO_2}/a), can only be reached when CO_2 capture and storage (CCS) is deployed. Without CCS, emissions from the energy system will stagnate at +6–8 Mt_{CO_2}/a which corresponds to a total GHG emissions of +10–16 Mt_{CO_2}/a. Negative emissions are realized when CO_2 is captured from waste incineration plants (50 % is biogenic) and especially when wood is gasified to hydrogen that is in turn used for freight mobility or industrial process heat. In addition, CCS needs to be applied to cement plants and possible gas turbine power plants. The total amount of stored CO_2 will be in the order of 15–20 Mt_{CO_2}/a.

Second, electricity generation and consumption increases compared to today's levels, mainly due to the electrification of the demand sectors heating and mobility. Besides hydropower, the main sources are new renewables (mostly photovoltaics), and thermal power plants. CCS needs to be applied on the latter if they are fueled by fossil natural gas.

Figure 16a shows the time evolution of electricity generation and consumption for the Imagine scenario variant at -6 Mt_{CO_2}/a emissions (representing a full year in 2050 with 24 typical days). PV generation peaks in summer at noon. These peaks are absorbed by a number of technologies on the consumption side:

1. pumped hydro storage ■ shifts electricity from day to night
2. heat pumps ■ generate domestic heat and store it in short-term or seasonal thermal energy storage
3. industrial electric heaters ■ supply process heat to industry, again with the help of thermal energy storage

A further possibility that was not explicitly modelled is the smart charging of electric vehicles.

The top graph shows the level of the alpine storage reservoirs which is increased for the progressive technology scenario compared to today (see Table 1). This allows to shift more hydropower ■ from summer

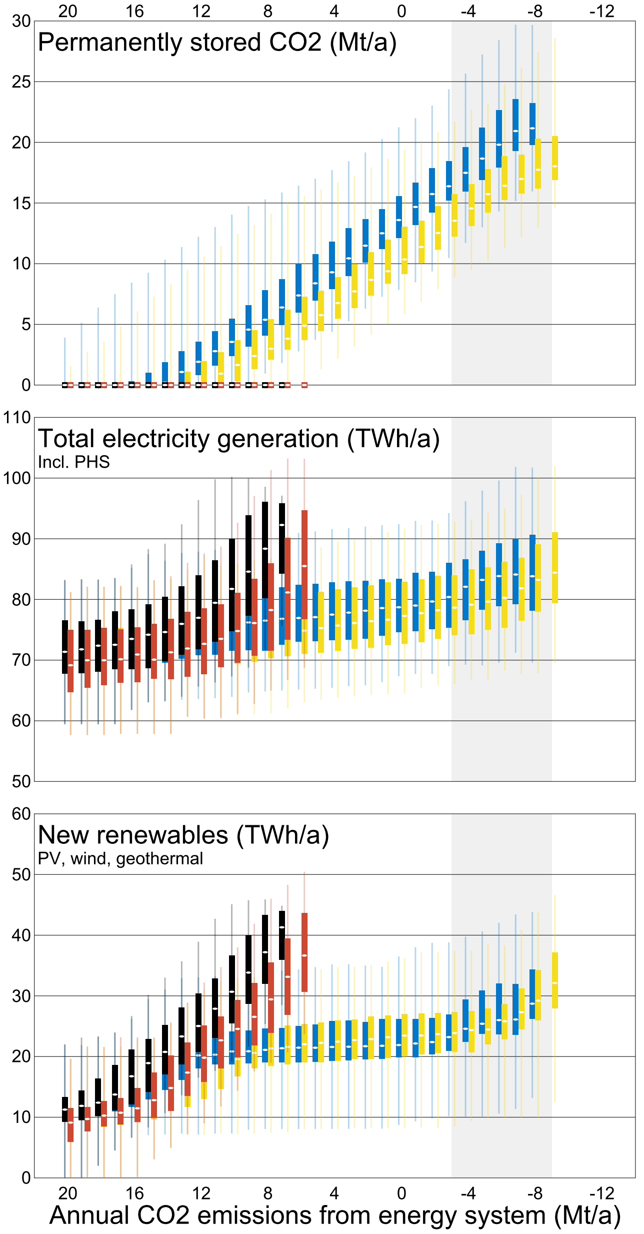


Figure 15: *Selected results for the scenario variants.*

to winter. The higher demand of electricity in winter is supplied by thermal power plants ■.

Figure 16b shows the supply and consumption of heat, including space heating, hot water and industrial process heat. The dominant technology is heat pumps ■ followed by thermal installations (combustion and CHP) burning fossil fuels ■ or biomass and waste ■. The peaks in the production side for heat pumps and electric process heaters ■ correspond to the consumption side of electricity (Figure 16a).

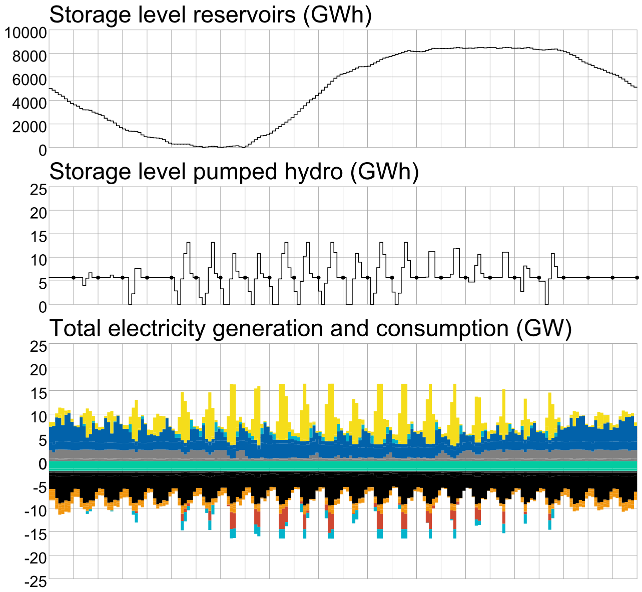
Hence, the excess electricity generation (beyond the demand) ■ is stored in short-term and seasonal thermal energy storage ■. In particular, seasonal thermal storage, helps balancing the electricity system by avoiding extra demand from heat pumps in winter. Other sources of low temperature heat are solar- ■ and geothermal ■.

The full set of results can be found in Guidati et al. (2021b). The most important recommendations from the probabilistic assessment using the SES-ETH model are:

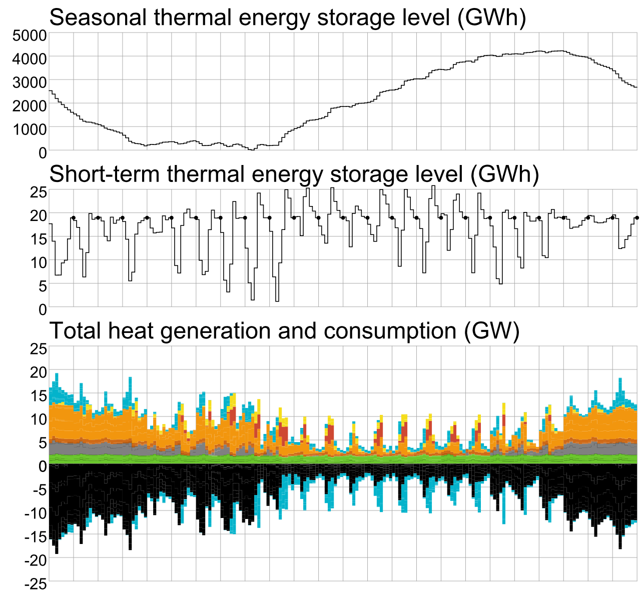
We need a CO_2 capture, transport and storage infrastructure. To reach the Swiss net-zero GHG emissions target, the energy sector (electricity, heat, mobility, including emissions from calcination in cement plants) will need to reduce its CO_2 emission from 38.3 Mt_{CO_2}/a in 2015 to negative levels of -4 to -8 Mt_{CO_2}/a in 2050. This is only possible by capturing and storing CO_2 from the existing 6 cement and 30 municipal waste incineration plants, from possible gas turbine combined cycles, and from wood gasification and natural gas reforming plants, that deliver hydrogen and CO_2. Since part of the primary energy entering these plants is biogenic in nature, this approach allows for negative emissions that can compensate the unavoidable emissions. The total amount of stored CO_2 will be around 15–20 Mt_{CO_2}/a (around 1.5–2 t_{CO_2} per capita). Since current studies show that Switzerland does not have sufficient domestic storage capacity, the country should actively contribute to the growth of an European CO_2 transport and storage infrastructure.

Biomass and hydrogen, two key elements of a net-zero strategy. Hydrogen plays a dual role in the future Swiss energy system. It allows to decarbonize those parts of road transport that cannot be easily electrified (e.g. heavy duty freight transport), and it can supply high temperature process heat to industry. At the same time, it can generate negative emissions during production, when using biomass as primary energy. This is the case for wood gasification and biogas reforming, both coupled with CCS. Wood is an important source of renewable energy and of biogenic CO_2. Its potential is not fully exploited by burning it for the purpose of residential heating, instead, it should be used to generate negative emissions, i.e. to extract CO_2 from the atmosphere and to store in in the subsurface. This can be achieved by wood gasification to hydrogen or by wood power plants equipped with CO_2 separation.

We need new sources of primary energy. Deep geothermal and solar thermal energy are valuable additions to the energy system and should be devel-



(a) *Electricity production and consumption.*



(b) *Heat production and consumption.*

Figure 16: *Time evolution throughout a year in 2050 using 24 typical days in the Imagine scenario variant for a target of -6 Mt_{CO_2}/a.*

oped for district heating, low temperature industrial processes and new processes such as the desorption step in CO_2 separation.

Industrial process heat will have to completely abandon the use of fossil oil and gas. For medium temperatures, geothermal and solar thermal is an interesting option to be explored. If the source temperature does not reach the level required for the process, high temperature heat pumps should be used. High temperature process heat can be generated using hydrogen or waste. Direct electrical heating is an interesting option that can exploit the strong photovoltaic generation in summer. It has to be coupled with thermal storage, either short-term (hours to days) or even better seasonal.

Large scale seasonal thermal energy storage helps to seasonally balance the energy system. Heat can be collected in summer with solar collectors, large scale heat pumps and industrial electric heaters that use excess photovoltaic generation. Despite the issue of expensive land in Switzerland, well-developed seasonal storage options like open-pit storage should be demonstrated with private and public partners.

Photovoltaic generation will have to grow by a factor of 10 compared to the levels of 2020. A close integration with the other demand sectors and the use of storage will be needed to properly manage the daily to seasonal fluctuations of PV. Integrating PV in buildings during the design phase will be mandatory, this will require the development of standardized products to be used by architects and civil engineers.

Efficiency measures and the electrification of heating and mobility is a crucial step in any decarbonization scenario. Heat pumps must become the standard to deliver space heat and domestic hot water. Electro-mobility will have to supply the largest share of mobility services, supported by hydrogen fuel cell vehicles. As a consequence, electricity consumption will increase to 70–90 TWh/a. Efficiency measures in the residential sector and in industry is generally found to be a cost effective means to reduce CO_2 emissions.

Figure 17: *Location of the study site, Baden Nord, Switzerland.*

4.5 Energy Hub Optimization Baden Nord

The results of the full energy system models give valuable insights that must lead to action, however, many of the specific measures – especially related to heating – have to be adapted to the local circumstances. Within JASM, this step from national to local scale was done in an exemplary way for the city of Baden. The aim was to identify optimal technological scenarios for the area of Baden Nord (Figure 17), with a focus on technical feasibility and costs. This was achieved in a two step approach:

1. Multi-energy demand modelling to estimate the future demand patterns for the area, and
2. energy hub optimization to identify a set of optimal energy supply solutions for the given site, representing different levels of sustainability performance.

For the energy demand modelling, Regionalwerke Baden (RWB) provided various datasets pertaining to the buildings and energy consumption in the study area. Hourly building energy demand profiles were subsequently calculated using the urban energy simulation tool CESAR (Wang et al., 2018). In the energy hub optimization, a multi-energy supply system optimization was carried out using Empa's *Ehub Tool* (Bollinger and Dorer, 2017). Figure 18 shows the technologies, resources and energy demands included in the analysis. The optimization proceeded in 3 phases:

1. the aggregated analysis identified an optimal energy supply options for the site as a whole, given the full range of available options
2. the sensitivity analysis determined the influence of different uncertain developments on the future optimal energy supply solution for the site
3. the detailed analysis identified the optimal supply technology locations and thermal network structures

The following conclusions were drawn from the results of this analysis:

The least cost solution for meeting the heating demands of the site is with district heating (SiBaNo), complemented by air-source heat pumps and rooftop PV installations.

If district heating is not a feasible solution (e.g. due to lack of available heating energy in the winter months), the least cost solution for meeting heating demands is with a combination of technologies, including a biomass boiler, gas CHP and oil boilers.

A 75 % reduction in operational CO_2 emissions with respect to the least cost solution can be achieved through a shift to heating supply primarily based on a biomass boiler. As in the least-cost solution, this is complemented by air-source heat pumps and rooftop PV installations. The resulting life-cycle costs are found to be ca. 7 % higher in comparison with the least cost solution.

Air-source chillers combined with groundwater-based freecooling is the most cost-effective and sustainable solution for meeting on-site cooling demands. If groundwater availability and temperature is sufficient, a purely groundwater-based (free)cooling solution is found to be most efficient.

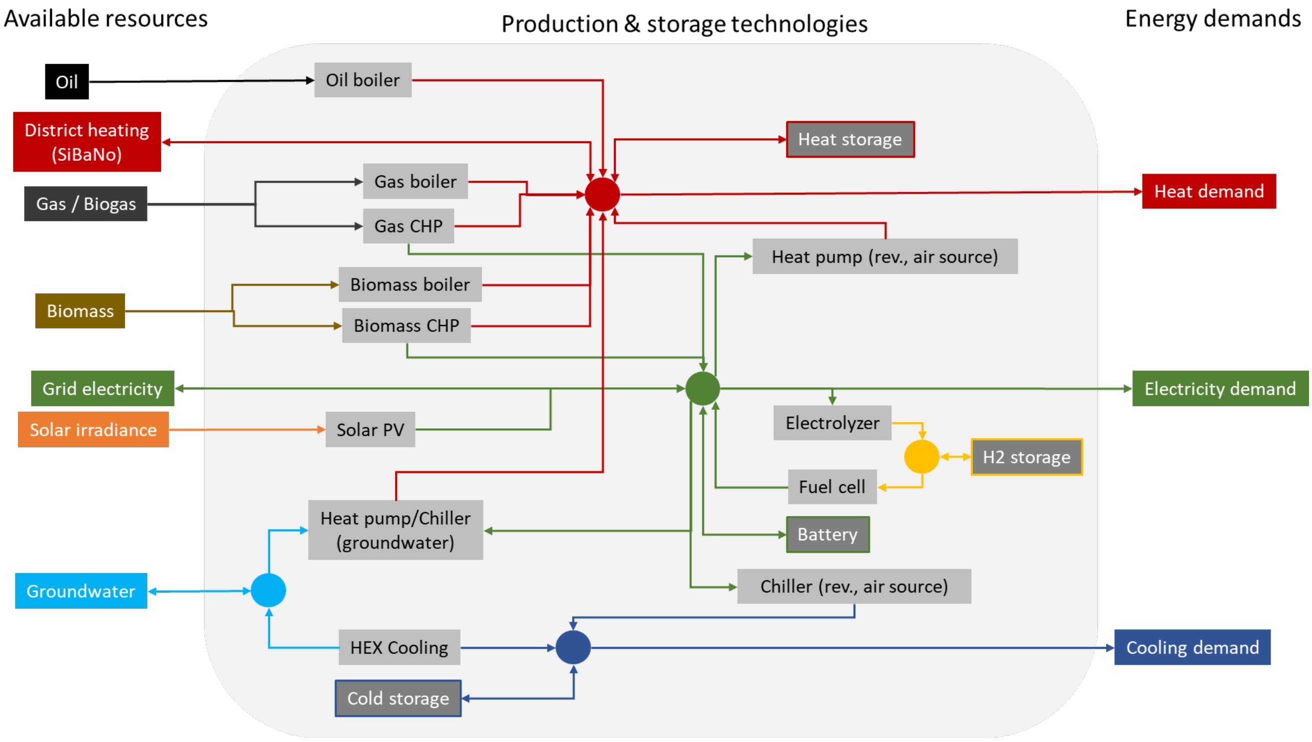


Figure 18: *Production & storage technologies and energy pathways considered in the analysis.*

5 Conclusions

Reaching net-zero greenhouse gas emissions in Switzerland is possible but it requires the combination of complementary and relevant policy measures and actions today that will allow the transformation of the energy system from different perspectives. In this section we present the policy recommendations derived from the common trends in the results from the energy-system models in JASM.

We used different energy system models to determine how Switzerland can reduce its GHG emissions to net-zero by 2050. This section presents a synthesis of selected results, highlighting the commonalities and explaining the differences. We put a spotlight on electricity generation, hydrogen production, the amount of stored CO_2, the total quantity of imported energy and the use of electricity in the mobility sector. Additional details can be found in the respective scenario reports of the single models (see also Section 4).

As explained in Section 4.1, STEM modelled the CLI scenario (C) to determine a cost-optimal trajectory for 0 Mt_{CO_2}/a within the energy system in 2050. In addition, four variants of CLI were considered:

- Fragmented global policy (**ANTI** (A)): This variant assumes an international context with low cooperation in mitigating climate change, and limited access to domestic renewable resources.
- Energy security (**SECUR** (S)): This variant builds upon ANTI, by assuming the same fragmented climate change policies worldwide but a Swiss society that is keener in using domestic renewable resources to reduce the carbon intensity of the Swiss economy and minimize import dependency.
- Market integration (**MARKETS** (M)): This storyline has a higher global cooperation and integration of the Swiss and international energy markets beyond the levels assumed in the core scenarios, while it also assumes increased access to domestic renewable resources.
- Technology innovation (**INNOV** (I)): This variant builds upon MARKETS by considering the same developments regarding the integration of energy markets and by additionally assuming that there is a global effort to mitigate climate change and achieve the Paris Agreements that also results in increased research and development expenditures to improve the performance of renewable and low-carbon technologies.

The SES-EPFL model targeted at -6 Mt_{CO_2}/a, with a variation of input parameters as shown in Figure 14 ■. SES-ETH developed a Monte Carlo variation of key parameters for different variants on market integration and technology development: Yesterday, Revolution, Come Together and Imagine (Table 1) and for a range of CO_2 targets from 20 to -10 Mt_{CO_2}/a (only energy system). In this synthesis, we combined the two scenario variants Imagine and Come Together with a variant of Imagine that allows for unlimited electricity imports at 100 CHF/MWh into a single probability distribution ■. The figures on the next pages compare the results from the various models. We also added the 2015 status at 38.4 Mt_{CO_2}/a as a reference ●.

5.1 Annual Electricity Use and Generation

Electricity use will increase due to the electrification of the transport and heating sectors. Using more efficient appliances and processes is key but does not compensate for the large increase driven by electric vehicles and heat pumps. Figure 19 (a) shows that this increase will be in the order of 10–20 TWh/a compared to the 2015 level.

Concerning electricity generation, photovoltaics will be the dominating new electricity source, contributing some 15–35 TWh/a (see Figure 19 (b)). Despite the significant role of new renewables (mostly photovoltaics), the strong increase in electricity demand will also require for thermal power generation and imports that are especially needed in winter months. Whenever fossil fuels are used, carbon capture and storage is mandatory.

5.2 Energy Imports

In 2015 Switzerland imported 74 % of its primary energy, mostly in the form of oil, nuclear fuels and natural gas. All models find that the value of more than 200 TWh/a will drop significantly to 30–50 TWh/a, which means an import share of 15–20 % in total primary energy supply (see Figure 19 (c)).

Imports of oil and nuclear fuels disappear completely by 2050. Natural gas stays at a lower level than today. The remaining imports are electricity and synthetic fuels, either from biological sources or based on hydrogen electrolysis with subsequent synthesis to hydrocarbons (e-fuels). The SECUR variant (S) results in almost 0 % import dependency, but it requires increased deployment of domestic solar PV also for producing synthetic e-fuels, which in all the rest of scenarios and variants are imported. In summary, "simple" energy carriers as nuclear fuel or oil are replaced by high-value carriers such as electricity or synthetic fuels.

5.3 Carbon Capture and Storage and the Role of Biomass

All models find that reaching net-zero emissions requires carbon capture and storage of at least 9 Mt_{CO_2}/a (see Figure 19 (d)). Current studies show that this storage potential is not available in Switzerland (Diamond, 2019). Therefore, we find it key to create a Swiss CO_2 collection network and to link it to a European transport network that will transfer the captured carbon to storage sites in the North Sea or elsewhere.

CO_2 capture must be applied to waste incineration and cement plants, and possibly to gas turbine power plants. Additional negative emissions need to be generated by using biomass technologies with carbon capture and storage, including wood gasification to hydrogen or synthetic natural gas, or combustion of biomass in power plants with tail end CO_2 separation. All these technologies have been available for some time, but were never at commercial scales. This will change with the drive towards net-zero emissions.

5.4 Hydrogen

Despite a considerable scatter within the various modelling results, hydrogen is used by all models for non-electric transport (person and freight) and for power and heat generation (see Figure 19 (e)). Differences in the results concern the details of production. The available technologies are electrolysis, gas reforming and wood gasification. These technologies appear in different proportions for the three models.

Wood gasification is the dominant technology for SES-ETH, it delivers also negative CO_2 emissions. Gas reforming with CCS is also used, whereas electrolysis is absent from the mix.

Wood gasification is also present in SES-EPFL, however, not to produce hydrogen but synthetic natural gas. This is driven by the assumption that CO_2 can be captured at the tail-end of a combustion process, making negative emissions possible also without the route via hydrogen. Consequently, the amount of hydrogen for SES-EPFL is lower, and it is produced mostly through electrolysis.

STEM features a mix of all three technologies with electrolysis accounting for approx. 50 %. STEM analyzes the 0 Mt_{CO_2}/a, which given its lower stringency requires fewer negative emissions and, therefore, the model results in lower levels of wood gasification.

The key takeaway is hydrogen will play a role in the future energy system, as an:

- energy source for transportation, power and heat;
- to generate negative emissions through biomass processing;
- and as an option to use excess summer electricity through electrolysis.

We recommend a broad approach of developing alternative hydrogen production technologies instead of focusing on electrolysis only.

5.5 Electro-Mobility

Figure 19 (f) shows the amount of electricity used for the transport sector (passenger and freight). This value will increase considerably from today's level and it will reach 15–20 TWh/a. Both the 2015 and the 2050 numbers include also rail transport. The value for SES-EPFL is slightly lower than for SES-ETH since it allows for a larger share of electric public passenger transport that is more energy-efficient than battery electric vehicles.

5.6 Efficiency Measures

The results from the energy system models show that retrofitting the buildings in both the residential and the commercial sectors is cost-efficient. However, according to the findings in Streicher et al. (2020a), the current budget allocated to retrofit subsidies, covers just about 5–7 % of the total investment cost needed to obtain the energy savings potentials. Additional funding programs to overcome the barrier of high upfront investment costs for energy retrofitting should be put in place to obtain the needed energy savings.

5.7 System Costs

All three models perform a cost optimization. Therefore, the additional costs that are related to a net-zero scenario can be estimated, albeit with the caveat that we modelled an inelastic demand and did not consider the impact on the full economy via a Computable General Equilibrium (CGE) model.

The STEM model evaluated the extra costs of the net-zero CLI scenario vs. the business as usual (BAU) scenario. The results show a cost of 97 billion CHF_{2010} over the period of 2020–2050, discounted at 2.5 % social discount rate, or 163 billion CHF_{2010} undiscounted. In terms of average capita cost per year this translates to 330 CHF_{2010}/a discounted, or 540 CHF_{2010}/a undiscounted. By considering the variants of CLI as well, the obtained range of the cumulative cost from STEM from 2020 to 2050 is 59–257 billion CHF_{2010} cumulative discounted at 2.5 %, or 97–426 billion CHF_{2010} cumulative undiscounted. This translates to an average per capita cost from 200–860 CHF_{2010}/a discounted, or 330–1430 CHF_{2010}/a undiscounted, over the period of 2020–2050. It should be noted that the per capita costs are averaged over the investigated time horizon until 2050, which is characterized by a fundamental transformation of the energy system and new technology and fuel mixes. The associated annual policy costs increase exponentially over the projection period, meaning that by 2050 we have built a more expensive energy system, which will require endured investments and expenditures for low carbon energy supply and demand also beyond 2050. The SES-ETH snapshot model estimated the extra costs in 2050 vs. a scenario where no CO_2 emissions reduction target is imposed to be 5–7 billion CHF_{2010}/a which correspond to 500–700 CHF/a per capita.

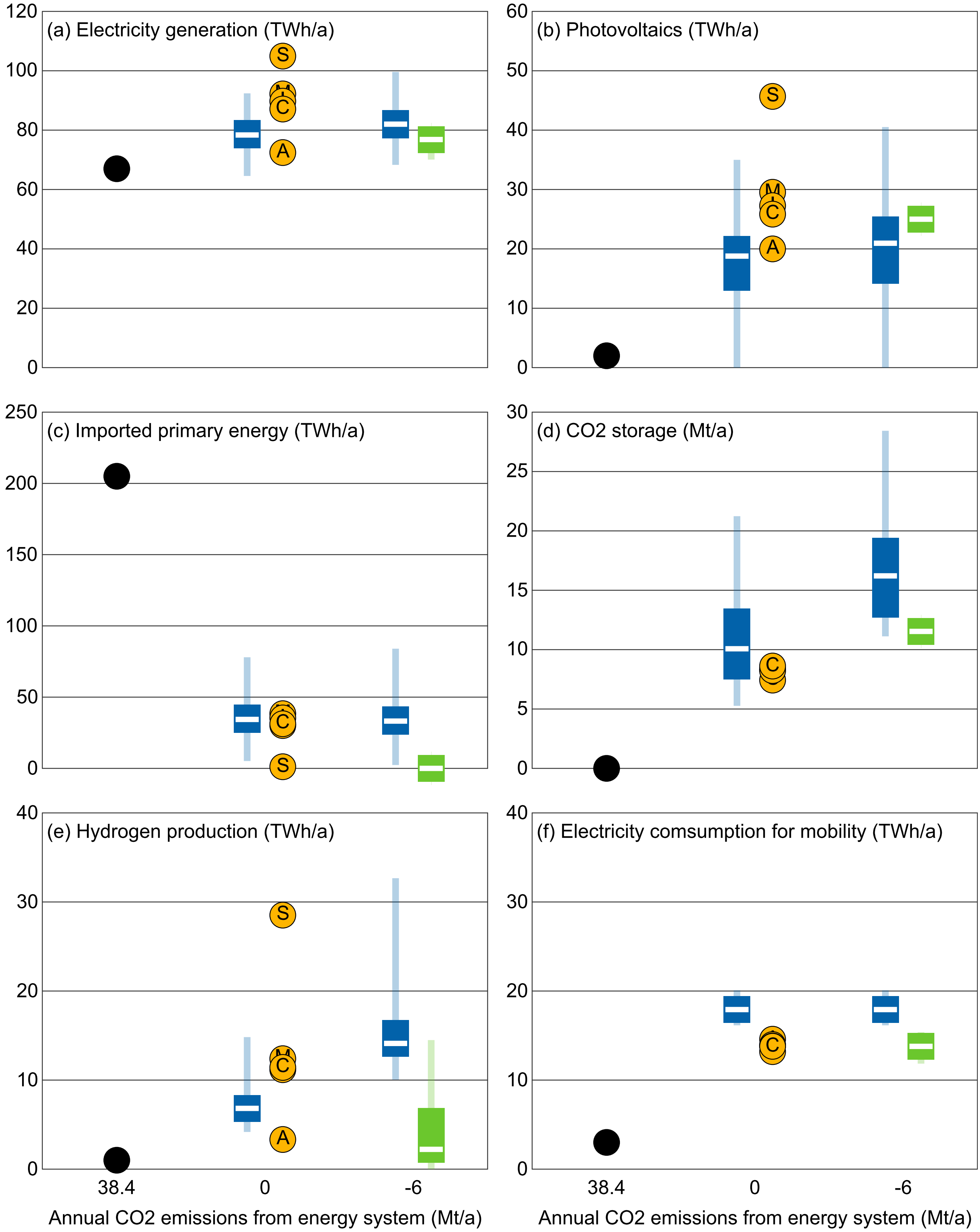


Figure 19: *Results from energy system models; 2015 (38.4 Mt_{CO_2}/a) and in 2050 (0 and -6 Mt_{CO_2}/a).*

6 Recommendations

The JASM Framework brought together several energy modeling research teams, which can be seen as unique in its kind for Switzerland. The teams joined forces and expertise to define and analyze scenarios for reaching net-zero GHG emissions in Switzerland by 2050, in a highly comprehensive way profiting from the combination of the wide spectrum of competences and experiences of the participating teams. The JASM framework proved the importance of cooperation and knowledge sharing among Switzerland's research community that increased the quality of the achieved results and paved the way for future work to overcome current limitations.

Expanding the framework beyond energy systems and sectoral models. The work in JASM was primarily carried out using sectoral and bottom-up energy systems models. These models are very detailed in the representation of technologies, the different energy sectors and their interdependencies. However, they are limited in capturing endogenously broader socioeconomic effects related, for example, to expenditures to human capital and education, reduced health impacts from air pollution, depletion of natural resources, broader economic and labor market impacts, changes in the welfare, etc. Moreover, the energy transition results in implications for agriculture, as well as to forests, lakes and eco-systems. To account for the effects of the energy transition and perform a rigorous cost-benefit analysis of tackling climate change, the modelling toolbox would need to be expanded in future work beyond energy and techno-economic models and include macro- and socioeconomic models, as well as models addressing non-energy sectors impacts such as related to agriculture, forests, water, etc.

Increasing the spatial resolution. JASM made a major effort to incorporate spatially detailed modelling, for instance, related to modelling of buildings and distribution grids. The analysis performed in JASM highlighted the value of spatially disaggregated analyses aligned with national modeling. Nevertheless, continued modeling efforts would be valuable to introduce higher spatial resolution modeling in several analytical tools. Besides capturing technical constraints related to the availability of the decarbonization options, location and anchor zones, or access to resources, many of the key technologies deployed to reach net-zero emissions require developing (new) infrastructures and an efficient coordination in policy planning between the State, Cantons and Communities. Cost-optimal solutions found at national levels need to be concretized and validated at lower scales, as the city-level case study within the JASM Framework showed. Increasing the spatial resolution would also provide a more accurate estimate on the infrastructure deployment costs.

Assessing European and International energy markets. One of the main findings in JASM is the need for imported zero- and low-carbon energy carriers, such as electricity, hydrogen, biofuels and synthetic e-fuels. These resources will be in high need in the context of a globally coordinated effort to mitigate climate change, with implications in their availability and supply costs to Switzerland. The JASM research team based the relevant scenario assumptions on well-established European and international outlooks from the IEA and other sources. While this is a valid approach, it would be desirable to expand the Swiss-focused modelling framework to include European (and global) energy markets modelling to provide energy market boundary conditions of Switzerland in an international context in a flexible and fully harmonized setting. In a future continuation of a JASM-type framework, it would be beneficial to improve consistency and increase the insights gained from the analysis, including the assessment of the uncertainties related to changing international energy market conditions.

Integrating social norms and consumer behaviour. Social practices and norms, as well as consumer behaviour, have a significant influence on technology choices and energy consumption patterns. The JASM research team tried to integrate different levels of social acceptance in the variants and uncertainty analysis performed with the energy systems models. However, there was a need for a stronger representation of the social and human factor in the analysis of the energy transition as key aspects of it, e.g. rebound effects, social justice or efficient social management of costs, could not be fully assessed. In future work, participation of researchers dealing with the social energy agenda could provide additional and valuable insights on technology acceptance, suitable policy measures, and more generally on social impacts and benefits of the energy transition.

Improving data quality, especially for new technologies needed for decarbonization. The JASM framework established a transparent data platform using peer-reviewed data regarding energy supply and demand technologies. Many of the essential technologies for decarbonization are today either at a lab-scale or at a demonstration phase which indicates significant uncertainties concerning technical performance and costs, which ultimately strongly affects the overall costs of energy transition. Continued research efforts are needed to improve the data quality used in the modelling frameworks, focusing on critical options such as CCS, CO_2 storage potentials, storage, synthetic fuels and smart use of energy. Moreover, efficiency and energy conservation measures play a critical role in decarbonizing the energy system. Within JASM a particular emphasis was placed on renovation in residential buildings and energy conservation in key industries.

Integrating international aviation. The JASM work did not deal with the developments in international aviation as this sector is currently excluded from the national climate protection goals and falls under the responsibility of ICAO (International Civil Aviation Organization) of the UN, which sets emissions standards and offsetting measures. In contrast, domestic aviation is captured under the NDCs. In case of the future inclusion of the international aviation to NDCs, the options to decarbonize the sector or offset its emissions with negative emissions projects would need to be assessed.

Emphasizing resilient energy systems. Sustainable and resilient energy systems will be the key topic in future analyses of deep decarbonization pathways. While the JASM framework included an adequacy study, more research is needed addressing resilience by anticipating new energy uses and shifting demands. Also, more detail in addressing the security of supply is required and across several dimensions, i.e. reliability of domestic infrastructure (partially addressed in JASM) and diversification and availability of energy imports (which has not been performed in JASM). Adaptation measures were assessed to a limited extend in JASM via climate impacts on heating/cooling demands and hydropower availability that required deployment of alternative measures and technologies from the models. Adaptation measures could be on focus on the political agenda in the years to come and relevant to the topic of resilience and recovery from a climate change shock.

Emphasizing sustainability in energy transition. The energy transition may potentially generate benefits within and beyond the energy system. Regarding sustainability, the JASM framework did not address externalities of the energy system related to impacts on ecosystems and human health, resource depletion or accident risks. Thus, the implications of energy transition on externalities were not accounted for in the quantification of costs; this should be included in the future holistic model-based analyses. Quantification of external and total costs is a prerequisite for carrying out cost-benefit analysis while Multi-criteria Decision Analysis (MCDA) enables broader inclusion of social aspects in sustainability assessment of technologies and scenario-based pathways as well as accounting for different stakeholder preferences when evaluating sustainability.

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